# Journal of the Royal Society of Western Australia

ISSN 0035-922X

## CONTENTS

Page

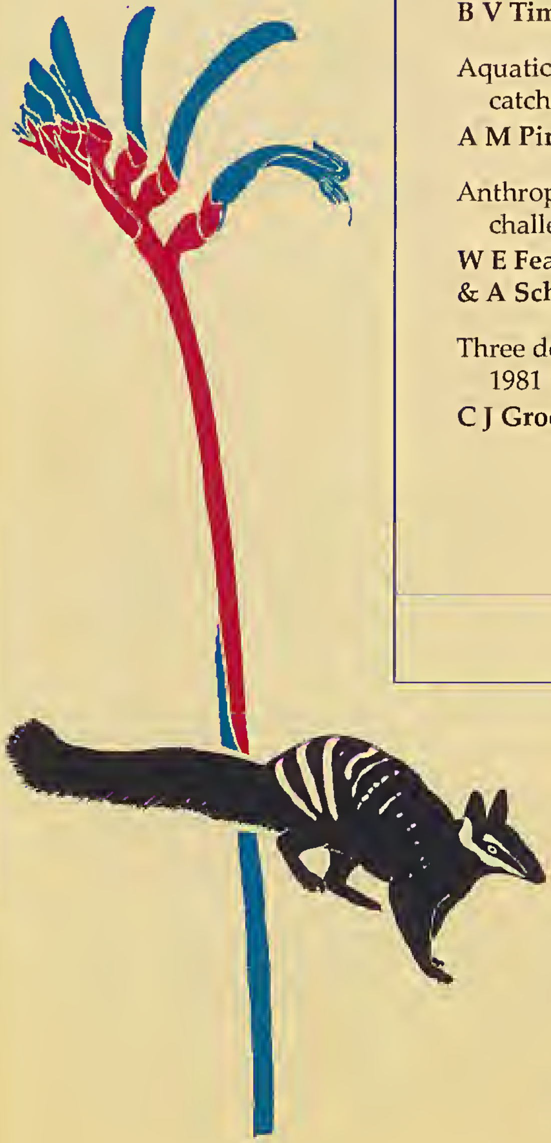
Ecology and life-cycle of a *Nitella* sp. from Capel Wetlands, Western Australia
**I Annan & J John** 1

Seasonal study of aquatic invertebrates in five sets of latitudinally separated gnammas in southern Western Australia
**B V Timms** 13

Aquatic invertebrates of the Hutt River and Hutt Lagoon catchments, Western Australia
**A M Pinder, K Quinlan, D J Cale & A E Leung** 29

Anthropogenic land subsidence in the Perth Basin: challenges for its retrospective geodetic detection
**W E Featherstone, M S Filmer, N T Penna, L M Morgan & A Schenk** 53

Three decades of cetacean strandings in Western Australia: 1981 to 2010
**C J Groom & D K Coughran** 63



Volume 95 Part 1
April 2012

# The Royal Society of Western Australia

To promote and foster science in Western Australia

**Patron**

Her Majesty the Queen

**Vice-Patrons**

His Excellency Mr Malcolm J McCusker, AO CVO QC
Governor of Western Australia

Professor Lyn Beazley AO FTSE MA PhD

---

## COUNCIL 2011–2013

**President** P O'Brien
**Immediate Past President** L Milne
**Vice-President** H Bekle
**Vice-President** K Trinajstic
**Hon Secretaries**
  **Council** L Milne
  **Membership** J Rosser
  **Proceedings**
**Hon Treasurer** P O'Brien
**Hon Editor** A E Cockbain
**Hon Librarian** P Clifford
**Journal Manager**
**Councillors**
  A W R Bevan
  L Collins
  C Florides
  M Gallegos
  W A Loneragan
  S Toby
  K Wright

## EDITORIAL BOARD 2011–2013

**Editor-in-chief**
A E Cockbain, South Perth
**Associate Editors**
H Bekle, Notre Dame University
A Bevan, Western Australian Museum
R Davis, Edith Cowan University
P Ladd, Murdoch University
K Trinajstic, Curtin University
M Van Keulen, Murdoch University

The Royal Society of Western Australia was founded in 1914. The Society promotes exchange among scientists from all fields in Western Australia through the publication of a journal, monthly meetings where interesting talks are presented by local or visiting scientists, and occasional symposia or excursions on topics of current importance. Members and guests are encouraged to attend meetings on the third Monday of every month (March – November) at 7 pm, Kings Park Board offices, Kings Park, West Perth, WA 6005, or as advertised, in the RSWA Proceedings, Diary of Events.

Individual membership subscriptions for the 2011/2012 financial year are $75 for ordinary Members, $40 for Student Members and $40 for Associate Members. For Library, company and institution subscriptions see the Society's website http://www.royalsocietyofwa.com. Prices include GST. For membership forms, contact the Membership Secretary, PO Box 7026, Karawara, Western Australia 6152, or visit the website http://www.royalsocietyofwa.com.

The Journal of the Royal Society of Western Australia was first published in 1915. Its circulation exceeds 650 copies. Nearly 100 of these are distributed to institutions or societies elsewhere in Australia. A further 300 copies circulate to more than 40 countries. The Society also has over 350 personal members, most of whom are scientists working in Western Australia. The Journal is indexed and abstracted internationally.

*Cover design*: The four subjects symbolize the diversity of sciences embraced by the Royal Society of Western Australia. Mangles' kangaroo paw (*Anigozanthos manglesii*) and the numbat (*Myrmecobius fasciatus*) are the floral and faunal emblems of Western Australia, and stromatolites are of particular significance in Western Australian geology (artwork: Jan Taylor). The Gogo Fish (*Mcnamaraspis kaprios*) is the fossil emblem of Western Australia (artwork: Danielle West after an original by John Long).

Journal of the Royal Society of Western Australia, 95: 1–11, 2012

# Ecology and life cycle of a *Nitella* sp. from Capel Wetlands, Western Australia

MUSEUM VICTORIA
18 SEP 2012

I ANNAN* & J JOHN†

*Department of Environment & Agriculture, Curtin University of Technology, GPO Box U1987, Perth, WA 6845*

* ✉ *ikeshun@yahoo.com*

† *Corresponding author* ✉ *J.John@curtin.edu.au*

The morphology, ecology, life cycle pattern and taxonomy of a *Nitella* sp., a charophyte from three sand-mine-void lakes at the Capel Wetlands Centre, were investigated both in the field and in the laboratory. Water depth was positively correlated with the height of the *Nitella* sp. Low numbers of gametangia were associated with high water depth. Life cycle of the charophyte was shown to be adapted to the hydrological regime and water quality of the temporary lakes at Capel Wetlands within the pH range of 5 to 9. Laboratory cultures of the species as well as its occurrence in lakes in the Perth Metropolitan region under various trophic conditions indicate that the species has wide ecological tolerance. The charophyte begins its life cycle with autumn rains filling the temporary wetlands and continues to grow throughout the winter. By spring, reproduction is initiated. Mature oospores are produced by the end of summer, coinciding with the decline in water level followed by the drying of the lakes. Morphology of vegetative and reproductive structures, reproductive state and ultrastructure of oospores were combined to provide a description of the species. The number of accessory branchlets was found to be variable. The *Nitella* species is placed under the subgenus *Decandollea* section *Decandollea* and shares characters of *N. congesta* (R Brown) A Braun and *N. lhotzkyi* A Braun.

**KEYWORDS: charophytes, ecology, life cycle, mine-voids, *Nitella congesta*, *Nitella lhotzkyi*, wetlands.**

## INTRODUCTION

Very little published information is available on charophytes of Western Australia. Most of the published works on Australian charophytes are from the Eastern States. Charophytes are pioneers of newly established wetlands (Zanereld 1940) and have been known for their ability to ameliorate water quality and increase productivity of wetlands (John 2003). As water quality of wetlands deteriorates, charophyte diversity tends to decrease (Blindow 1992a; van den Berg *et al.* 1998; Kufel & Kufel 2002). Identification of charophytes beyond the genus level often requires consideration of not only the morphology of the vegetative structure and arrangement and ultrastructure of reproductive bodies but also the monoecy or dioecy nature of reproduction. A *Nitella sp.* was found to have colonised a number of sand-mine-void wetlands at Capel, Western Australia in the early 1990s. The colonisation started from the bottom end of a chain of 15 lakes when the pH changed from 4 to 5. Colonisation of this charophyte was found to have significantly contributed to the development of the lakes at Capel Wetlands Centre. These wetlands were oligotrophic with high mineral content (John 2003; Annan 2008). The charophyte species in this study has been also found in Lake Leschenaultia and in many urban stormwater wetlands and artificial lakes (e.g. Lake Bungana in Maylands) around Perth. The range of aquatic environments occupied by charophytes, coupled with their response to lake restoration make them relevant in the management of wetlands (Coops 2002).

Charophytes include five distinct genera: *Chara*, *Nitella*, *Lamprothamnium*, *Lychnothamnus* and *Tolypella*. The genus *Nitella* is characterised by forked branchlets (furcation), compressed oospores, terminal antheridia and 10-celled coronula in the oogonium (Wood & Imahori 1965; Casanova 2009).

The growth and mortality of charophytes may be influenced by factors such as temperature, water depth, transparency, pH, flow, turbulence, the presence of herbivores, shading by other macrophytes, and nutrient concentrations in the water and sediment (Meiers *et al.* 1999; Casanova & Brock 1999). Charophyte growth rate differs according to substratum particles (Andrews *et al.* 1984a) water depth (Andrews *et al.* 1984b), and to some extent nutrient status (e.g. phosphorus concentration: Blindow 1988; Kufel & Kufel 2002). Charophytes can be classified as annuals or perennials depending on the life cycle pattern. They can be either monoecious or dioecious. In the monoecious species the male and female reproductive bodies are borne on the same individual, can be attached at the same node (conjoined) or at different nodes. Fertilized oogonia develop into oospores.

The ultrastructure of the oospore wall and sometimes supplemented by chromosome numbers is important in the identification of charophytes (John & Moore 1987; Casanova 1997, 2009; García, 1999, 2001, 2002; Sakayama *et al.* 2002, 2004, 2005). The oospore of charophytes is protected by a sheath of five spirally disposed cells known as the tube cells and when fertilised, develops a thick multilayered wall. Ridges, which ascend spirally from right to left are formed from the lower lateral walls of these spiral cells and later develop into a prominent flange or wing-like protrusion. The area of the wall lying between each spirally disposed ridge is called the fossa.

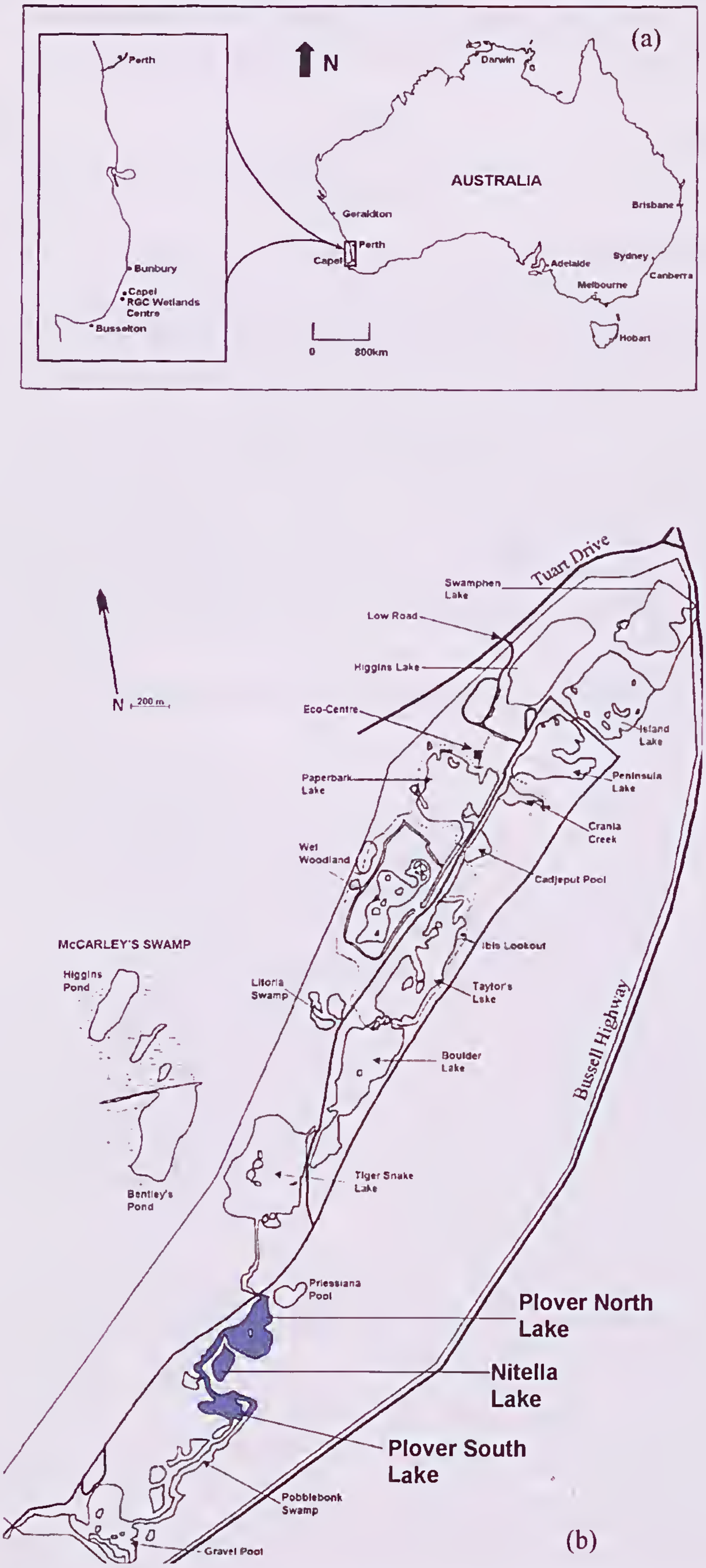


**Figure 1.** (a) Map of Australia showing site. (b) Chain of lakes that make up the Capel Wetlands Centre. The lakes coloured blue are the lakes selected for the project.

The fossa is often ornamented and this is a species-specific feature. Fully mature oospores have characteristic ornamentation, offering more reliable information than non-mature ones since the latter either lack, or have weakly developed, ornamentation (John & Moore 1987).

The objective of this paper is to report investigations on the morphology, life cycle, ecology and identity of a *Nitella* sp. from the Capel Wetland Centre, Western Australia by field and laboratory culture observations.

## MATERIALS AND METHODS

### Site description

The charophytes investigated were from Capel (33°S, 115°E), midway between the regional centres Bunbury and Busselton, 200 km south of Perth, Western Australia (Figure 1a). The annual average rainfall for the Capel region is 730.3 mm (Bureau of Meteorology 2008) and the climate is Mediterranean characterised by dry summers and wet winters. The region is originally comprised of mixed woodland interspersed with tuart groves, sandy areas of *Banskia* woodland and wet swampy areas with peaty edges (Davies 2002).

Since 1956, sand deposits, mainly titaniferous minerals ilmenite and rutile have been mined from Capel (Brooks 1991; Qui *et al.* 2002). The mining operations were extensive with the removal of large quantities of sand from the orebodies with, significantly, no backfilling. The pits created after the extraction of mineral sands intercepted the water table with the resultant formation of mine voids (pits) which were converted into artificial wetlands by landscaping and creating islands and peninsulas, and planting fringing vegetation between 1975 and 1979. The wetland lakes were originally used as a source for mineral processing. These lakes were acidic with pH ranging from 2 to 4.

A *Nitella* sp. was later found to have colonised a number of the interconnected linear chain of 15 lakes at the Capel Wetlands Centre. The first record of the *Nitella* sp. in the lakes was in the early 1990s in two lakes (John 1993). A study conducted in 1987 to assess the water quality of the wetlands indicated that the very low pH posed a problem impeding the development of the lakes. The low pH of the lakes was the result of the acidic effluent water discharged from the processing plant to the top lake in the chain of the mine-void lakes. The effluent was neutralised from 1988 to 1993 thus raising the average pH of the lakes to more than 7. In 1996, four more lakes were found to have been colonised by the *Nitella* species and in 2003, with further increase of pH, 12 lakes were recorded to have the charophyte (John 2003). Its presence was found to have significantly contributed to the development of the lakes at Capel Wetlands Centre. Three lakes, Plover North Lake, Plover South Lake and Nitella Lake, from a chain of mine-void wetlands all of which had abundant charophytes were chosen for this study (Figure 1b).

### Morphological studies

Samples of healthy charophyte shoots were collected from the field and washed to remove as much debris as possible and observed under a Leica dissection stereomicroscope. The shoots were excised from the apex downwards and various morphological features such as the main axis, branchlets, primary, secondary and dactyl cells were observed and measured. Both antheridia and oogonia were examined and their dimensions measured under dissection stereomicroscope and compound microscopes and micrographs taken as required.

### Scanning electron microscopy (SEM) of oospores

The ornamentation pattern of the oospore can be considered a highly reliable consistent character and therefore of a significant diagnostic feature (Boszke *et al.* 2008). For the genus *Nitella*, oospore morphology serves as an indicator in speciation in the absence of breeding studies (Casanova 2009). The oospores were cleaned for scanning electron microscopic observation using the acetolysis method after John & Moore (1987). The cleaned oospores were placed on glass slides and were heated on a hot plate at low heat, until all the water was evaporated. The oospores were then mounted on aluminium stubs with a double-sided transparent adhesive tape, sputter-coated with gold and viewed with a Phillip's XL 30 Scanning Electron microscope using secondary and backscattered electron detectors with an accelerating voltage of 15kV. Oospore characteristics were outlined following descriptions given by Wood & Imahori (1965), Haas (1994), Garcia (2001, 2002) and Casanova (2009).

### Growth studies in the field and laboratory

Charophyte samples were harvested monthly from May to November in 2004 from Nitella Lake, Plover North and Plover South Lakes at the Capel Wetland Centre. Measurement of height, number of nodes and number of branches were recorded for 25 individuals during each sampling. Height was measured from the apical meristem to the point of attachment of rhizoids. Nodes and branches were also counted along the axes for each individual. The growth measurements continued until the first sighting of reproductive bodies. Data on length were used to calculate mean growth rates taking elongation of the shoot as a proxy for growth in the field using formula 1 (below). One-way ANOVA was used to compare means of the three different groups (i.e. individuals from Nitella Lake, Plover North Lake and Plover South Lake) to find out whether there was any significant growth difference among the three lakes. Statistical package SPSS Grad Pack 15.0 was used for all the statistical analyses.

Sediment samples containing oospores of charophytes were collected from Nitella Lake, Plover North and Plover South Lakes (at a depth of ~30 cm and a distance of 1 m from the western banks) in 2004. The sediment samples were dehydrated by evaporation and equal amounts of sediment were transferred into three aquarium tanks (30 L glass tanks) in the greenhouse at the Department of Environmental and Agriculture, Curtin University of Technology. Twenty litres of lake water was added slowly to each tank. The aquaria were aerated with pumps and air-stones and left in natural day length conditions from 30 April to 30 November 2004 (244 days). Water levels were maintained by adding lake water.

The germination and growth of germinants were monitored. Measurement of height, number of nodes and branches were recorded for 20 individuals (selected at random and tagged loosely by carefully tied red-coloured thread around the thallus) from each tank. This was done from the onset of emergence of the germinants up to the first sighting of reproductive bodies. Height was measured from the apex of the thallus to the upper surface of sediment where charophyte rhizoids were located. The number of nodes and branches were counted along the axes of tagged individuals. One-way ANOVA was used to compare means of the three different groups to see whether there were any statistically significant differences. The growth rates $G_r$ (mm/day) were calculated from the shoot length data using the formula:

$$G_r = \frac{H_t - H_0}{t} \qquad (1)$$

where $H_0$ is the length of the shoot at time zero and $H_t$ is the length of the same shoot after a period of t days.

### Water depth vs height of *Nitella*

Two sites (one shallow and the other deeper) were selected from Plover South Lake (shallow, 33°36.19"S, 115°30.11"E and deep, 33°36.17"S, 115°30.25"E) in 2005 and the mean heights of the *Nitella* sp. shoots were measured against the water depth monthly from June to November. Plover South Lake was selected because it was the deepest among the three lakes for the study. Data obtained were subjected to regression analysis to determine any statistically significant relationship between water depth and height of *Nitella* sp. shoots.

### Life cycle studies of the *Nitella* sp. in the field and laboratory

The morphological changes of the *Nitella* sp. cultured were observed fortnightly in the field and on daily basis in the laboratory culture. Timing of production of gametangia (antheridia and oogonia) and the duration of their maturity were recorded. The reproductive bodies were collected, measurements taken and features viewed under a Leica stereomicroscope. Where possible, photographs of the stages were taken. Male and female shoots from the tagged samples in the culture tanks and from field samples were counted to determine the sex ratio.

Frequent monitoring of the water quality of the lakes were done during the duration of this study with additional sampling in 2008.

## RESULTS

### Morphological studies

The vegetative features of the *Nitella* sp. are illustrated in Figure 2(a). The apical meristem and the main axis are ensheathed by mucilage. From the apex (topmost whorl) downwards, the number of branchlets at the nodes varied. The number of branchlets from the 1st to 3rd nodes from the apex were consistently 8 (Figure 2b). However, from the 4th node, the number of branchlets changed. At the 4th node, in addition to the primary branchlets, accessory branchlets were seen either at developing or developed stages. The total number of branchlets at the 4th node ranged from 15 to 20. From the 4th node downwards to the rhizoids, the accessory branchlets were consistent and well developed. However, at the lowest part of the thallus, the accessory branchlets were absent. Additionally, the accessory branchlets were irregularly arranged in between the primary branchlets, some above and some below the node. The primary rays (labelled P in Figure 2i) were observed to furcate into 5 or 6 secondary rays. The secondary rays (labelled S in Figure 2k) terminated into 5–6 dactyls (labelled D in Figure 2k) which were 2-celled. The antheridia were solitary, orange coloured and had 8 shield cells, 375–450 μm in diameter and located terminally at the point of furcation (Figure 2f, g). Oogonia were gold coloured and 1–3 at points of furcation on female individuals (Figure 2h–m). They were 650–750 μm long and 400–500 μm wide with 7–9 convolutions. Coronula in 2 rows of 5 and were 30–45μm high and 50–60μm wide at the base.

### Oospore structure by SEM

Oospores were identified using the following parameters and descriptions. Results were compared with those of Wood & Imahori (1965), García (1999, 2001, 2002) and Casanova (2009). The length was 415–500 μm; width 300–400 μm and length:width ratio 1.0–1.6. The shape of the oospore is described from different views: apical view, flattened (Figure 3a); lateral view, compressed (Figure 3b); ridges are prominent, 7–9 in number (Figure 3b); basal view (Figure 3c); colour is light-brown but turns dark-brown when mature. The oospore membrane ornamentation is imperfect reticulate (Figure 3d).

### Growth studies in the field and laboratory

The highest growth rate in the field was observed in Plover South Lake in winter corresponding with the lowest mean temperature 18°C (Table 1). The mean

**Table 1** Field growth rate (mm/day) of *Nitella* sp. in Plover South, Plover North and Nitella Lakes with corresponding mean temperature (°C) in 2004. n = 25.

| | Plover South Lake (mm/day) | Mean Temperature (°C) | Plover North Lake (mm/day) | Mean Temperature (°C) | Nitella Lake (mm/day) | Mean Temperature (°C) |
|---|---|---|---|---|---|---|
| Autumn | 0.52±0.30 | 23.0 | 0.61±0.30 | 22.0 | 0.50±0.13 | 23.4 |
| Winter | 1.92±0.89 | 18.0 | 1.17±0.62 | 18.7 | 0.79±0.33 | 19.2 |
| Spring | 0.95±0.29 | 24.5 | 0.74±0.65 | 23.8 | 0.36±0.36 | 26.0 |

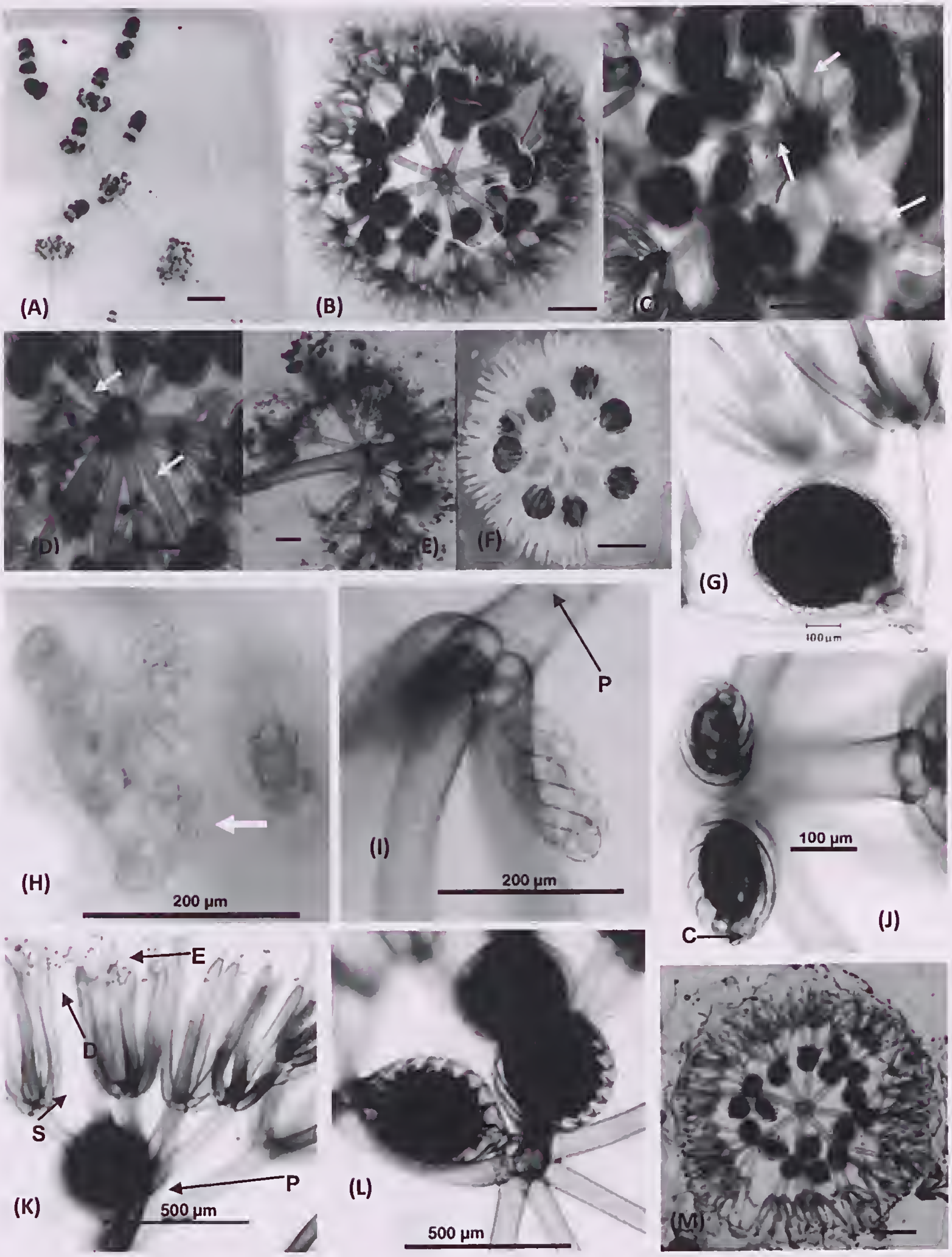


Figure 2. Morphology of *Nitella* sp. from Capel Wetlands. (a) Habit showing whorls of branchlets and internodes; towards the apex the internodes are compacted; whorls of branchlets spread out as mucilage was shed off. Scale bar, 5 mm. (b) Whorls of branchlets at third node without accessory branchlets. Scale bar, 500 µm. (c) Whorls of primary branchlets with developing accessory branchlets (three arrowed) at fourth node from the apex of thallus. Scale bar, 500 µm. (d) Whorls of primary branchlets and developed accessory branchlets (two arrowed) at fourth node from the apex of thallus. Scale bar, 500 µm. (e) Whorl of primary branchlets from the mid-portion of thallus with accessory branchlets. Scale bar, 1 mm. (f, g) antheridia (globules), male sex bodies. Scale bar, 400 µm. (h) Developing oogonia (nucules) showing five tube cells. Top view of the coronula cells (arrowed). (i) Developing oogonium at point of furcation of a primary branchlet/ray. P, primary branchlet/ray. (j) Fertilised oogonia at a point of furcation of a primary branchlet. C, coronula of 10 cells in two tiers. (k) Developing oospores at a point of furcation of a primary ray. P, primary ray; S, secondary ray; D, dactyl; E, end cell. (l) Mature oospores at points of furcation of primary rays. (m) Whorl of oogonia with outer covering mucilage. Mucilage was stained with toluidine blue. Scale bar, 450 µm.

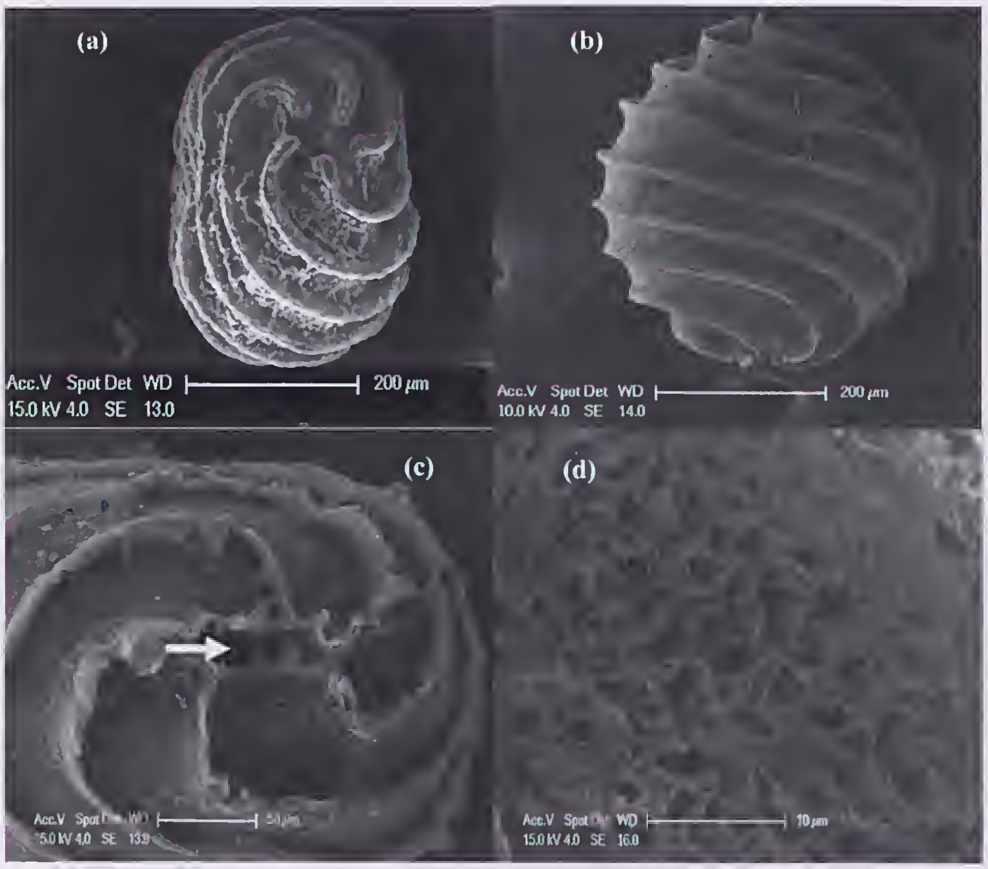


**Figure 3.** Oospore of *Nitella* sp. (a) Apical view of oospore of *Nitella* sp.. (b) Lateral view of oospore showing ridges or flanges with fossa. (c) Basal view of oospore of *Nitella* sp. showing basal plug (arrowed). (d) Oospore wall showing imperfect reticulate ornamentation.

height, mean number of nodes and mean number of branches of shoots in the field were also highest in the Plover South Lake (Table 2). In the laboratory, the highest growth rate was in the Plover North Tank in winter corresponding with the lowest temperature of 12°C (Table 3). The mean height, mean number of nodes and mean number of branches of the *Nitella* sp. in the laboratory was also highest in the Plover North Tank (Table 4). Overall, growth rates were higher in the field than in the laboratory. *Nitella* sp. showed tolerance for high pH, conductivity and salinity in the field (Table 5) and laboratory (Table 6). However, when the lakes became acidic (pH 3.47–4.28) in 2008, no charophytes were observed.

**Table 2** One-way ANOVA comparing mean height, mean number of nodes and mean number of branches per shoot of *Nitella* sp. in the field in 2004. $\alpha = 0.05$, n = 25.

| | Plover South Lake Mean±sd | Plover North Lake Mean±sd | Nitella Lake Mean±sd | F | *P* |
|---|---|---|---|---|---|
| Mean height (mm) | 159.20±110.47 | 124.38±77.18 | 83.86±47.02 | 1.69 | 0.21 |
| Mean number of nodes | 10.59±4.80 | 9.47±4.09 | 4.61±2.14 | 4.78 | **0.02*** |
| Mean number of branches | 4.21±3.00 | 1.53±1.39 | 1.40±0.70 | 4.60 | **0.02*** |

**Table 3** Laboratory growth rate (mm/day) of *Nitella* sp. in aquaria with corresponding mean temperature (°C) in 2004. n = 20.

| | Plover South Lake (mm/day) | Mean Temperature (°C) | Plover North Lake (mm/day) | Mean Temperature (°C) | Nitella Lake (mm/day) | Mean Temperature (°C) |
|---|---|---|---|---|---|---|
| Autumn | 0.47±0.30 | 20.3 | 0.50±0.37 | 21.2 | 0.26±0.16 | 22.2 |
| Winter | 0.67±0.12 | 14.1 | 1.01±0.11 | 12.0 | 0.59±0.26 | 13.7 |
| Spring | 0.22±0.14 | 23.2 | 0.07±0.10 | 27.7 | 0.43±0.34 | 25.8 |

**Table 4** One-way ANOVA comparing mean height, mean number of nodes and mean number of branches per shoot of *Nitella* sp. in the laboratory in 2004. α = 0.05, n = 20

| | **Plover South Lake Mean±sd** | **Plover North Lake Mean±sd** | **Nitella Lake Mean±sd** | **F** | ***P*** |
|---|---|---|---|---|---|
| Mean height (mm) | 54.53±17.33 | 98.56±40.85 | 41.76±24.82 | 1.82 | 0.19 |
| Mean number of nodes | 8.57±2.09 | 12.69±4.84 | 7.84±2.50 | 4.21 | 0.03* |
| Mean number of branches | 0.84±0.69 | 1.37±1.12 | 0.75±0.56 | 1.16 | 0.34 |

**Table 5** Water-quality parameters measured in the field during growth of *Nitella* sp. in 2004 and 2008.

| **Parameter** | **Plover South Lake** | | **Plover North Lake** | | **Nitella Lake** | |
|---|---|---|---|---|---|---|
| | **2004** | **2008** | **2004** | **2008** | **2004** | **2008** |
| pH | 7.94–9.15 | 3.47 | 7.88–8.25 | 6.25 | 8.04–8.94 | 4.28 |
| Conductivity (μScm$^{-1}$) | 1232–2290 | 1542 | 1174–1462 | 1820 | 268–782 | 822 |
| Salinity (ppm) | 604–1069 | 787 | 408–699 | 941 | 125–378 | 410 |

**Table 6** Water-quality parameters measured in the laboratory during growth of *Nitella* sp. in 2004.

| **Parameter** | **Plover South Lake** | **Plover North Lake** | **Nitella Lake** |
|---|---|---|---|
| pH | 9.05 | 8.85 | 9.13 |
| Conductivity (μS/cm) | 2640 | 2460 | 1440 |
| Salinity (ppm) | 1338 | 980 | 781 |

### Water depth vs height

Regression analysis of water depth and mean height per shoot of *Nitella* sp. in Plover South Lake Site 1 was significant at the 5% level. F = 148.13, R Square = 97.4%, P = 0.00 (Figure 4). Regression analysis of water depth and mean height per shoot of *Nitella* sp. in Plover South Lake Site 2 was significant at the 5% level. F = 35.86, R Square = 90.0%, P = 0.00 (Figure 5). The high R-square values showed that the height of *Nitella* sp. was associated with water depth. The deeper the water, the higher the height of shoots observed.

### Life cycle studies of the *Nitella* sp. in the field and laboratory

This species was found to be dioecious, producing separate male and female reproductive structures on separate individuals. The male individuals produced orange-coloured octoscutate antheridia (with eight shield cells) and were borne terminally. This occurred within a period of 2–4 weeks after which no more antheridia were seen. The oogonia which were initially somewhat gold coloured, were observed to have become dominant two weeks after the development of the antheridia. After 3–5 weeks of production of the oogonia, oospores were observed. The oospores reached maturity with a colour change to dark-brown during summer.

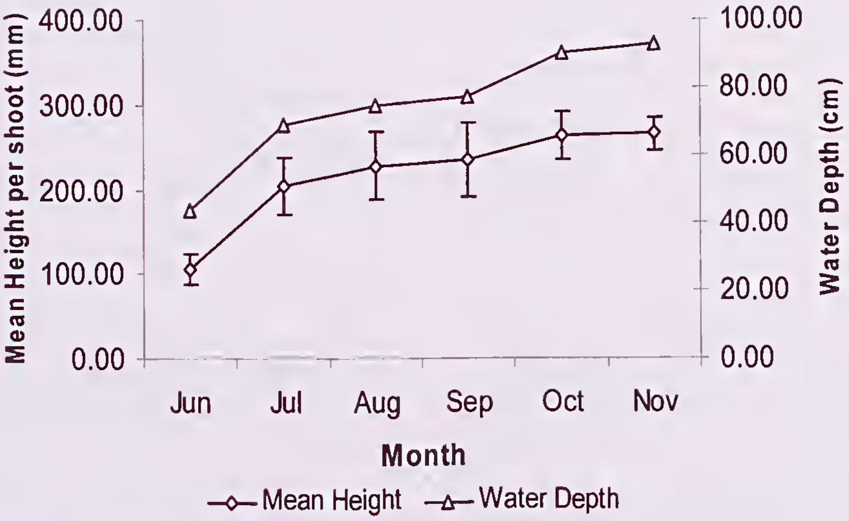


**Figure 4.** Mean height of shoot of *Nitella* sp. in Plover South Lake Site 1 (deep).

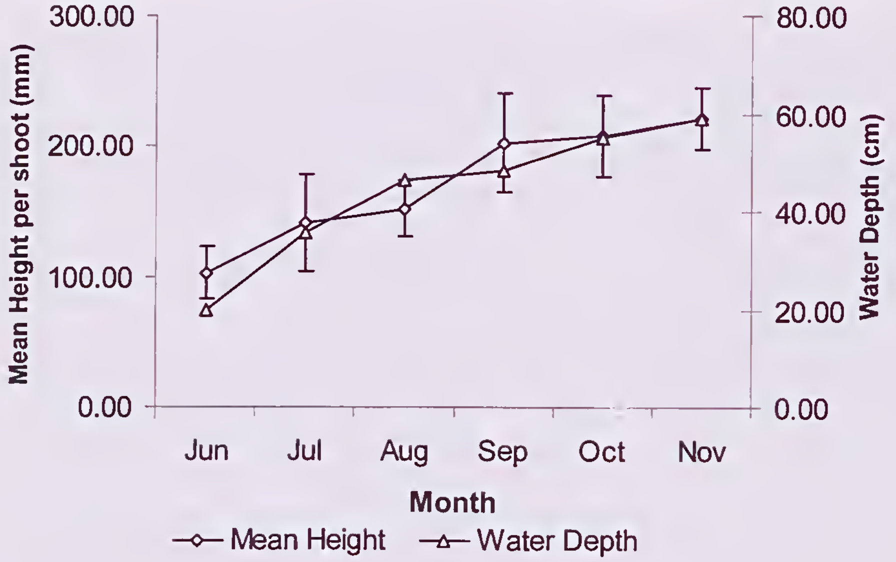


**Figure 5.** Mean height of shoot of *Nitella* sp. in Plover South Lake Site 2 (shallow).

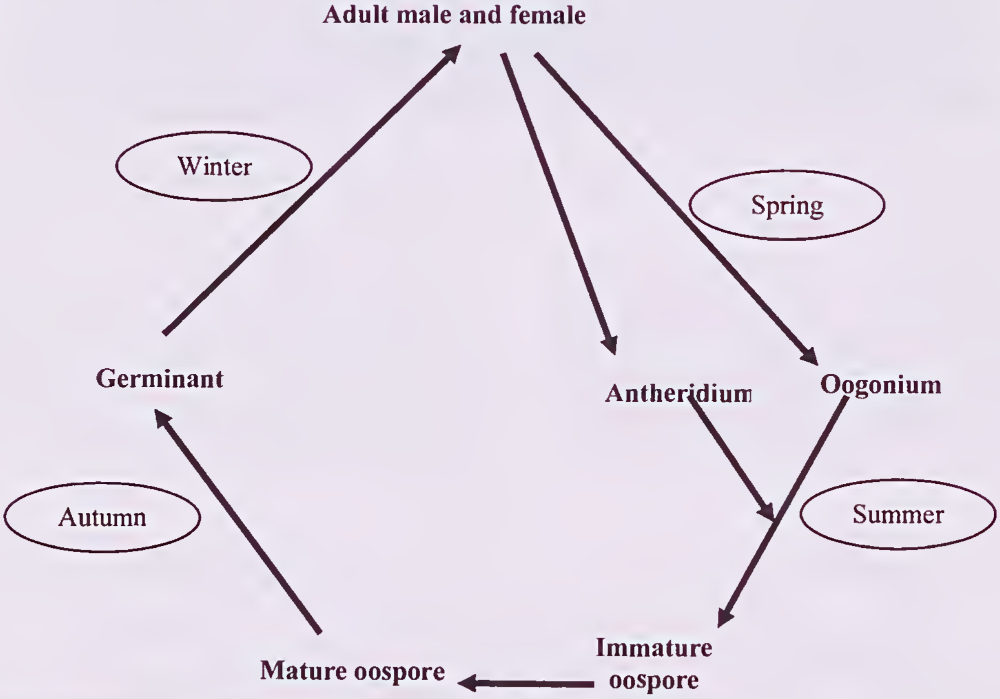


**Figure 6.** Schematic representation of the life cycle of *Nitella* sp. in relation to seasonal changes.

In the field study, the charophyte again showed vegetative growth for approximately 25 weeks before undergoing reproduction. The production of reproductive bodies was observed from late October to early November (late spring). Ratio of male to female individuals in all three lakes was ~1:1 with no statistical difference among lakes or between field-grown and cultured populations. A schematic presentation of the life cycle of the *Nitella* sp. summarising the observations is shown in Figure 6.

## DISCUSSION

### Morphological studies

The charophyte resembles closely *Nitella hyalina, Nitella lhotzkyi* and *Nitella congesta* (placed in the subgenus *Decandollea* by Casanova (2009) in vegetative morphological features and share characteristic mucilage ensheathment over the meristem and axis. This species in Capel Wetlands was initially identified as *N. hyalina* in previous studies before the lifecycle was investigated

(John & Gayton 1994; Ward *et al.* 1997; John 2003). *N. lhotzkyi* produces mucilage ensheathment over the apical meristem and most of the vegetative body. However, *N. hyalina* is monoecious, while *N. congesta* and *N. lhotzkyi* (Wood & Imahori 1965) are dioecious. In comparison with *N. lhotzkyi*, the branchlets with the mucilaginous ensheathment at nodes on the axis of *N. congesta* are spheroid and compact which has also been observed in the current species. However, in *N. lhlotzkyi*, the branchlets are found to be of two kinds in each whorl (Wood & Imahori 1965) and consistently spread out: normal branchlets are 7–11 in a whorl with only 1 or 2 furcation and the accessory branchlets are consistently present at each node on the entire thallus (Wood & Imahori 1965). The current *Nitella* sp. was found to have consistently 8 primary branchlets at each node and the branchlets are not spread out in two rows as in *N. lhotzkyi*, although the accessory branchlets are irregular and shorter than the primary branchlets.

In the population of *Nitella* studied, the accessory branchlets could not be observed as a consistent feature at all nodes. This made identification of species very difficult. However, careful observations showed that the accessory branchlets develop later at some nodes away from the tip (apical meristem) of the thallus. It was observed that many new branchlets were being produced in between the primary branchlets. From our observations, it is clear that as the growth proceeds, more accessory branchlets would be produced from the top downwards. However, there is no mention about the sequential development of accessory branchlets from the top downwards in the literature. Whether the variability in the accessory branchlets is a plastic character is unknown. Examination of specimens collected from an artificial eutrophic wetland from Maylands, in the Perth region, clearly show the accessory branchlets developing from the 3rd to 4th node from the apex up to a maximum number of 20 accessory branchlets.

Another characteristic feature was the shape of the oogonium. The shape of the oogonium in the current species is similar to that of *N. congesta* as described by Wood & Imahori (1965). Wood & Imahori (1965) also described the oospore membrane ornamentation of *N. lhotzkyi* as finely granulate and that of *N. congesta* as 'slightly spongy'. The current species of Nitella has a reticulate oospore ornamentation. The oospore-based determination of some species of charophytes still remains very difficult (Boszke *et al.* 2008). According to Casanova (1997), morphological variations of the charophyte oospores can be associated with the type of ecosystems. Plasticity in the development of charophyte morphology has been documented in several studies (Küster *et al.* 2004; Schneider *et al.* 2006). Therefore based on observed morphological features compared with those in the literature, the species in this paper appears to be close to *Nitella congesta* (R Brown) A Braun. The low number (20) of accessory branchlets appears to separate the Capel populations from those described by Wood & Imahori (1965), van Raam (1995), García (1999) and Casanova (2009).

### Growth of *Nitella* sp.

Charophytes have a range of growth strategies (Blindow 1992b; Titus *et al.* 2004). Perennial growths have been reported in deep lakes, while in temporary water bodies, growth may be seasonal (Pentecost *et al.* 2006). New individuals do develop from the internodes of decaying individuals beneath the sediment surface or from germinating oospores. The vegetative growth rate of the *Nitella* sp. appeared to be seasonal, highest in winter. There was average rapid increase in height of shoots as well as number of nodes and increase in internode distance in winter. During spring, the charophyte undergoes sexual reproduction beginning with the production of antheridia and oogonia on different individuals, water level playing a significant role in the survival and reproduction. In the laboratory, *Nitella* sp. showed initiation of reproductive bodies when the water levels in the aquaria were left to decrease considerably. The initiation of reproductive bodies started between late August (26 August 2004) and the end of September (30 September 2004) (late winter to early spring) with the increase in temperature, eventually resulting in the drying out of the temporary lakes. Therefore resources might have been channelled to the production of fruiting bodies in sexual reproduction on the onset of increasing temperature. The highest growth in terms of height, number of nodes and number of branches in Plover South Lake could be the result of the depth of the lake; it was the deepest among the three lakes. Thus vegetative growth was very pronounced in that lake.

### Ecology and life cycle of the *Nitella* sp.

Charophytes are sensitive to water-quality parameters, especially pH (García 2002). From this study the lower limit of pH of this species was found to be between 3.5 and 5. This species of *Nitella* showed tolerance to high conductivity.

After fertilization, the zygotes underwent maturity as temperature rose during late spring and early summer. At that stage, the oospores became darker and shrank in size (mature oospore). Oospores were then released into the sediment as the standing water dried out. Thus, the life cycle of the *Nitella* sp. was well adapted to the hydrological regime of the lakes. The production and release of oospores was triggered to coincide with the summer drawdown, depositing the oospores in the sediment to ensure species success. On the onset of rains during late autumn/early winter, mass germination of oospores was observed. That was followed by a slow period of growth and then accelerated vegetative growth and finally reproductive phase.

Charophyte life history is characterised by monocarpy or polycarpy based on the reproductive patterns of the alga. Polycarpic charophytes reproduce several times in a lifetime whereas monocarpic ones reproduce once and die. Monocarpics are divided into those that reproduce at an early stage and grow for a long time and those that grow vegetatively for some time before undergoing reproduction and then death (Harper 1977; Casanova 1993). In this study, the *Nitella* sp. exhibited the latter type of monocarpy in the laboratory cultures and in two of the Capel lakes which are typically temporary. Thus the *Nitella* sp. acted as an annual in the temporary wetlands. However, in the deepest lake, Plover South Lake (with a depth of about 2.5 m) had sparse reproductive bodies and continued to grow vegetatively. This can be interpreted as an indication of the adaptability of the *Nitella* sp. in deep waters to survive as a facultative monocarpic species.

Sex allocation in charophytes is complicated and is influenced by geographical and environmental factors (Cox 1981; Lloyd 1982). The male shoots became the most abundant followed by the female shoots becoming the most abundant later. This protandrous phenomenon has been explained as a temporal niche separating sexes (Cox 1981). The production of antheridia before that of oogonia presupposes that it may be less expensive to produce antheridia than oogonia (Casanova 1994). Therefore assuming that the production of antheridia required fewer resources than that for oogonia, antheridia were produced earlier than oogonia. Charophytes can reproduce by asexual means, for example, by the generation of secondary protonema from the bulbils in permanent water bodies. In this case, the plant energy is allocated toward vegetative growth instead of sexual reproduction. In ephemeral water bodies on the other hand, charophytes reproduce by sexual means whereby drought resistant oospores are produced. Thus more resources are allocated towards oospore production rather than vegetative growth (Casanova 1994).

### Description of *Nitella* sp. from Capel Wetlands Centre, Western Australia

Wood (1972) mentioned the occurrence of the species in Victoria and Western Australia. An illustration of the vegetative and reproductive structures of the species is given in Wood & Imahori (1965). A description of the *Nitella* sp. from Western Australia based upon populations at Capel is presented below.

The alga is dioecious, mostly up to 33 cm high but more than 1 m in deeper lakes and dark green in colour with slender axes, 0.7–1.0 mm in diameter. There were 8 primary branchlets (3.0–7.0 mm long) at each node but up to 20 branchlets where accessory branchlets were present. The accessory branchlets are irregularly arranged. Apical part of shoot was covered with mucilage making it compact (Figure 2a). The internode lengths varied according to water depth; shorter towards the apical meristems and longer downwards along the axis. The primary rays furcate into secondary rays (length 1.0–2.3 mm which are 5–6 in a whorl (reduced when replaced by an oogonium), one being percurrent. The secondary rays furcate into 5–6 dactyls which are 2-celled; end cell transparent in the population studied. They were elongated, 100–200 µm long (including acuminate end cell). Both the internode and whorls of branchlets are ensheathed by mucilage. As mucilage is shed off in the lower portion of shoot, branchlets appear to spread out (Figure 2c). Accessory branchlets were found at some 3 nodes below the terminal meristem in between normal branchlets. Oogonia are 1–3 aggregated at nodes, 650–750 µm long, 400–500 µm wide and with 7–9 convolutions. Coronula are 30–45µ high and 50–60µ wide at the base. Antheridia are solitary, terminal on males (Figure 2f), 375–450 µm in diameter. Oospores are light-brown or dark-brown (when fully mature), 415–500 µm long, 300–400 µm wide; striae of 7–9 broad, prominent ridges with an imperfect reticulate ornamentation.

In conclusion, based upon mucilaginous ensheathment, vegetative morphology, structure of gametangia, oospore structure and sexual state, the population of *Nitella* sp. in Capel Wetlands and some Perth wetlands treated in this paper could not be placed either in *N. congesta* or *N. lhotzkyi*. Casanova (2009) provided the most up-to-date overview of *Nitella* in Australia and summarised the characters of the subgenera of *Nitella*. Accordingly, this species can be placed in the subgenus *Decandollea* and section *Decandollea* to which the above two species of *Nitella* have been allotted. However, of all the subgenera of *Nitella*, *Decandollea* remains problematic (Casanova 2009). Further work is required to delineate species boundaries within the section.

## ACKNOWLEDGMENTS

We wish to thank the Department of Environment and Agriculture, Curtin University for providing facilities and funding for the experiments and field trips which were part of a PhD project. We also thank Ann Bentley of the Capel Wetlands Centre for her assistance, Peter Mioduzweski for his technical assistance in the several field trips, Adriana García (University of Wollongong) for her assistance in taxonomy and two anonymous referees for their helpful suggestions. Finally we would like to express our appreciation to Kathy Meney for her encouragement and dedicated service to the Journal of the Royal Society of Western Australia for many years.

## REFERENCES

Andrews M, Box R, McInroy S & Raven J A 1984b. Growth of *Chara hispida*. II. Shade adaptation. *Journal of Ecology* **72**, 885–895.

Andrews M, Davison I R, Andrews M E & Raven J A 1984a. Growth of *Chara hispida* I. Apical growth and basal decay. *Journal of Ecology* 72, 873–884.

Annan I K E 2008. *Nitella congesta*—a charophyte as a tool for the rehabilitation of sand mine-void wetlands at Capel, Western Australia. PhD thesis. Curtin University of Technology, Perth (unpubl.).

Blindow I 1988. Phosphorus toxicity in *Chara*. *Aquatic Botany* **32**, 393–395.

Blindow I 1992a. Decline of charophytes during eutrophication: comparison with angiosperms. *Freshwater Biology* **28**, 9–14.

Blindow I 1992b. Long and short term dynamics of submerged macrophytes in two shallow eutrophic lakes. *Freshwater Biology* **28**, 15–27.

Boszke P Pelechaty M & Pukacz A 2008. Oospore dimensions and wall ornamentation in *Chara braunii*. Biologia **63**, 457–460.

Brooks D 1991. Progressive development of the RGC Wetlands Centre, Capel, Western Australia. *RGC Wetlands Centre Capel Technical Report* **17**.

Bureau of Meteorology 2008. Climate statistics for Australian locations – Bunbury Region. <http://www.bom.gov.au/climate/averages/tables/cw_009965.shtml>

Casanova M T 1993. The ecology of charophytes in temporary and permanent wetlands. PhD thesis. University of New England, Armadale (unpubl.).

Casanova M T 1994. Vegetative and reproductive responses of charophytes to water-level fluctuations in permanent and temporary wetlands in Australia. *Australian Journal of Marine and Freshwater Research* **45**, 1409–1419.

Casanova M T 1997. Oospore variation in three species of Chara (Charales, Chlorophyta). *Phycologia* **36**, 274–280.

Casanova M T 2009. An overview of *Nitella* (Characeae, Charophyceae) in Australia. *Australian Systematic Botany* 22, 193–218.

Casanova M T & Brock M A 1999. Life histories of charophytes from permanent and temporary wetlands in eastern Australia. *Australian Journal of Botany* **47**, 383–397.

Coops H 2002. Ecology of charophytes: an introduction. *Aquatic Botany* **72**, 205–208.

Cox P A 1981. Niche partitioning between sexes of dioecious plants. *American Naturalist* **117**, 295–307.

Davies S J J F 2002. The Capel Wetland Centre: a survey of its historical developments, significance and research results. *Curtin University of Technology School of Environmental Biology Bulletin* **22**.

García A 1999. Charophyte flora of south-eastern South Australia and south-western Victoria, Australia: systematics, distribution and ecology. *Australian Journal of Botany* **47**, 407–426.

García A 2001. Taxonomy and ecology of charophytes. 3rd Australian Algal Workshop, Brisbane, 2001.

García A 2002. Charophytes (stoneworts): taxonomy and ecology. 4th Australian Algal Workshop, Perth, 2002.

Haas N J 1994. First identification key for charophyte oospore from central Europe. *European Journal of Phycology* **29**, 227–235.

Harper J L 1977. *Population biology of plants*. Academic Press, London.

John J 1993. The use of algae in monitoring the development of RGC wetlands at Capel, Western Australia. *RGC Wetlands Centre Capel Technical Report* **19**.

John J 2003. Phycoremediation: algae as tools for remediation of mine-void wetlands. *In:* Ambasht R S & Ambasht N K (eds) *Modern trends in applied aquatic ecology*, pp. 133–147. Kluwer, New York.

John D M & Moore J A 1987. An SEM study of the oospore of some *Nitella* species (Charales, Chlorophyta) with description of wall ornamentation and an assessment of its taxonomic importance. *Phycologia* **26**, 334–355.

John J & Gayton C 1994. A comparative study of epiphytic diatom communities on aquatic macrophytes in two artificial wetlands. *RGC Wetlands Centre Capel Technical Report* **23**.

Kufel L & Kufel I 2002. Chara beds acting as nutrient sinks in shallow lakes—a review. *Aquatic Botany* 72, 249–260.

Küster A, Schaible R & Schubert H 2004. Light acclimation of photosynthesis in three charophyte species. *Aquatic Botany* 79, 111–124.

Lloyd D G 1982. Selection of combined versus separate sexes in seed plants. *American Naturalist* **120**, 571–585.

Meiers S T, Proctor V W & Chapman R L 1999. Phylogeny and biogeography of *Chara* Charophyta) inferred from 18S rDNA sequences. *Australian Journal of Botany* **47**, 347–360.

Pentecost A, Andrews J E, Dennis P F, Marca-Bell A & Dennis S 2006. Charophyte growth in small temperate water bodies: extreme isotopic disequilibrium and implications for the palaeoecology of shallow marl lakes. *Palaeogeography, Palaeoclimatology, Palaeoecology* **240**, 389–404.

Qui S, Scott B & McComb A 2002. Predicting effects of inflow diversion on future water levels in mining-created wetlands, Capel. *RGC Wetlands Centre Capel Technical Report* **53**.

Sakayama H, Hara Y & Nozaki H 2004. Taxonomic re-examination of six species of *Nitella* (Charales, Charophyceae) from Asia, and phylogenic relationships within the genus based on *rbc*L and *atp*B gene sequences. *Phycologia* **43**, 91–104.

Sakayama H, Miyaji K, Nagumo T, Kato M, Hara Y & Nozaki H 2005. Taxonomic re-examination of 17 species of *Nitella* Subgenus *Tieffallenia* (Charales, Charophyceae) based on internal morphology of the oospore wall and multiple DNA marker sequences. *Journal of Phycology* **41**, 195–211.

Sakayama H, Nozaki H, Kasaki H & Hara Y 2002. Taxonomic re-examination of *Nitella* (Charales, Charophyceae) from Japan, based on microscopic studies of oospore wall ornamentation and *rbc*L gene sequences. *Phycologia* **41**, 397–408.

Schneider S, Ziegler C & Melzer A 2006. Growth towards light as an adaptation to high light conditions in *Chara* branches. *New Phytologist* **172**, 83–91.

Titus J E, Grise D, Sullivan G & Stephens M D 2004. Monitoring submerged vegetation in a mesotrophic lake: correlation of two spatio-temporal scales of change. *Aquatic Botany* **79**, 33–50.

van den Berg M S, Scheffer M, Coops H & Simons J 1998. The role of characean algae in the management of eutrophic shallow lakes. *Journal of Phycology* **34**, 750–756.

van Raam J C 1995. *The Characeae of Tasmania*. Gebrüder Borntraeger, Berlin.

Ward M J, Zilm N & John J 1997. The role of charophytes, a group of submerged macrophytes in the rehabilitation of the RGC Wetlands Centre. *RGS Wetlands Centre Capel Technical Report* **35**.

Wood R D 1972. *Characeae of Australia*. Verlag Von J. Cramer, Lehre.

Wood R D & Imahori K 1965. *A revision of the Characeae*. Verlag Von J. Cramer, Weinheim.

Zaneveld J S 1940. The charophyta of Malaysia and adjacent countries. *Blumea* 4, 1–224.

*Received 1 February 2010; accepted 14 March 2012*

Journal of the Royal Society of Western Australia, 95: 13–28, 2012

# Seasonal study of aquatic invertebrates in five sets of latitudinally separated gnammas in southern Western Australia

**B V TIMMS**

*Australian Wetland and Rivers Centre, School of Biological, Earth & Environmental Sciences, University of New South Wales, Sydney, 2052.* ✉ *brian.timms@unsw.edu.au*

Gnammas (i.e. rock pools) are characteristic habitats on granitic inselbergs in southern Western Australia and, though their basic limnology is known, much remains to be learnt on the distribution patterns and seasonality of their fauna. In this study 10 pools on five inselbergs (Mt Madden, Hyden Rock, Yanneymooning Rock, Bullamanya Rock and Walga Rock) across a 700 km latitudinal climatic gradient were studied during the flooded period from May to October 2010. Seventy-three taxa inhabited the five rocks and showed declining species richness from south to north promoted by decreasing hydroperiod and reliability to the north. Passively dispersing crustaceans dominated with 47% of taxa, and almost all of the most abundant species, while 41% of taxa were seasonal colonising insects. Many pools had 25–30 invertebrate species each, far more than rock pools elsewhere in Australia and overseas. Most of the dominant species were widespread, more localised taxa included cyclopoids and the snail *Glyptophysa* sp. in the south and the notostracan *Triops* n. sp. in the north. Regional endemism and specialisation to live in gnammas was high as a consequence of past climatic changes linked with the role of these pools as refuges. Most of the dominant species were filter feeders on algae and allochthonous and autochthonous organic matter and the dominant predators were planarians and beetle larvae. Most species peaked in abundance in August and September, with large branchiopods (mainly the anostracan *Branchinella longirostris*) peaking before cladocerans and with ostracods last. Active dispersers included hemipterans, coleopterans and dipterans; almost all were widespread opportunists, but at least one *Paroster* beetle species was a gnamma specialist. Chironomids were dominated by gnamma specialists *Paraborniella tonneri* and *Allotrissocladius* sp 1 which survive the dry summer *in situ* as cryptobiotic 4th instars and emerge soon after the ponds first fill, and by the temporary pond specialist *Chironomus tepperi* which invaded from elsewhere when the ponds fill. Stones in the gnammas were important for at least two species: *Triops* n.sp uses them to hide from predators and the snail *Glyptophysa* aestivates underneath them. Succession in these pools was best explained by the tolerance model in which each taxon developed at its own pace, largely unaffected by other taxa.

**KEYWORDS: beetles, *Boeckella opaqua*, branchiopods, chironomids, cladocerans, latitudinal gradient, nematodes, ostracods, *Paroster*, planarians, rock pools, seasonal succession**

## INTRODUCTION

A number of surveys of pools on granite outcrops in southwestern Western Australia have revealed a diverse aquatic fauna with many endemic species and rock pool specialists (Jones 1971; Bayly 1982 1997; Pinder et al. 2000, Timms 2006; Jocqué *et al.* 2007a). Prominent amongst the crustaceans are branchiopods *Branchinella longirostris* and *Limnadia badia*, the copepod *Boeckella opaqua*, cladocerans *Daphnia jollyi, Macrothrix hardingi, Plurispina* spp., *Celsinotum* spp., and ostracods *Bennelongia* sp563, *Cypretta* spp, *Ilyodromus* spp., *Cypericercus* spp (all *sensu* Pinder *et al.* 2000). The most common insects are chironomids like *Allotrissocladius* spp and *Paraborniella tonnoiri* (Edward 1968) and some new species of *Paroster* beetles (Hendrich & Frey 2008). Distribution of taxa across the Wheatbelt and Goldfields is heterogeneous, especially for large branchiopods (Timms 2006) and unpublished studies (Jocqué 2007; B. Vanschoenwinkel *et al.* pers.comm. 2011) suggest a decline in overall species richness and change in community structure from south to north.

The Western Australian gnammas have been poorly characterised in terms of geomorphology, hydrology and successional patterns, but are broadly categorised into pan gnammas, pit gnammas and pipe (or cylindrical) gnammas (Twidale & Corbin 1963; Bayly *et al.* 2011; B V Timms unpubl. data). Most studies dealt almost exclusively with pan gnammas avoiding variation associated with distinctive but less speciose and different communities of pit and pipe gnammas (Bayly *et al.* 2011; B V Timms unpubl. data). Little is known about successional changes and regional variation in southwest Western Australia. Temporally constrained studies performed in early, mid or late successional stages or in localised areas could give unrepresentative results. Concerning the latter, Bayly's (1982) study of pools at Northcliffe, far to the south of the main Wheatbelt presented a reduced fauna than typical for Wheatbelt pools and the lack of some common dominants such as *Limnadia badia, Daphnia jollyi* and *Macrothrix hardingi,* while the large branchiopod *Caenestheriella mariae* seems to be mainly in gnammas fringing the northern and eastern wheatbelt (Timms 2006).

This study examines the association of successional stage on species richness and community composition of invertebrates in pan gnammas. Particular attention will be paid to when pool communities are the most speciose and whether or not there are major changes in community structure between early, mid and late stages of the pools' hydroperiod. In addition, pools were chosen on a long north–south gradient, in order to investigate the effect of climate on invertebrate distribution and population size in the pools.

## METHODS

Five granite outcrops, Mt Madden (33°14'22.6"S, 119°50'33.6"E), Hyden (=Wave) Rock (32°26'43.6"S, 118°54'14.4"E), Yanneymooning Rock (30°42'50.5"S, 118°33'19.2"E), Bullamanya Rock (29°09'50.9"S, 117°39'40.4"E) and Walga Rock (27°24'14.2"S, 117°27'48.8"E), were chosen roughly equidistantly along a north-northwest–south-southeast line ~700 km long (Figure 1). Ten pan gnammas on each rock ranging over various sizes from ~1 m diameter and ~8–12 cm deep to the largest available (often ~5 m diameter and 20–40 cm deep) were studied. A range of pool sizes was chosen to: (i) represent the variety found in nature; and (ii) cover the possibility of species richness being influenced by pool size (Bayly 1997). Most of the pools selected were within 100 m of each other near the summit of each rock, but some outliers were located downslope, thus extending the maximum distance between pools to ~250 m on Mt Madden, Yanneymooning and Bullamanya Rocks, and to ~150 m on Hyden Rock and Walga Rock. Sampling commenced on 24 May 2010, then at three-weekly intervals until early October and took 3–4 days

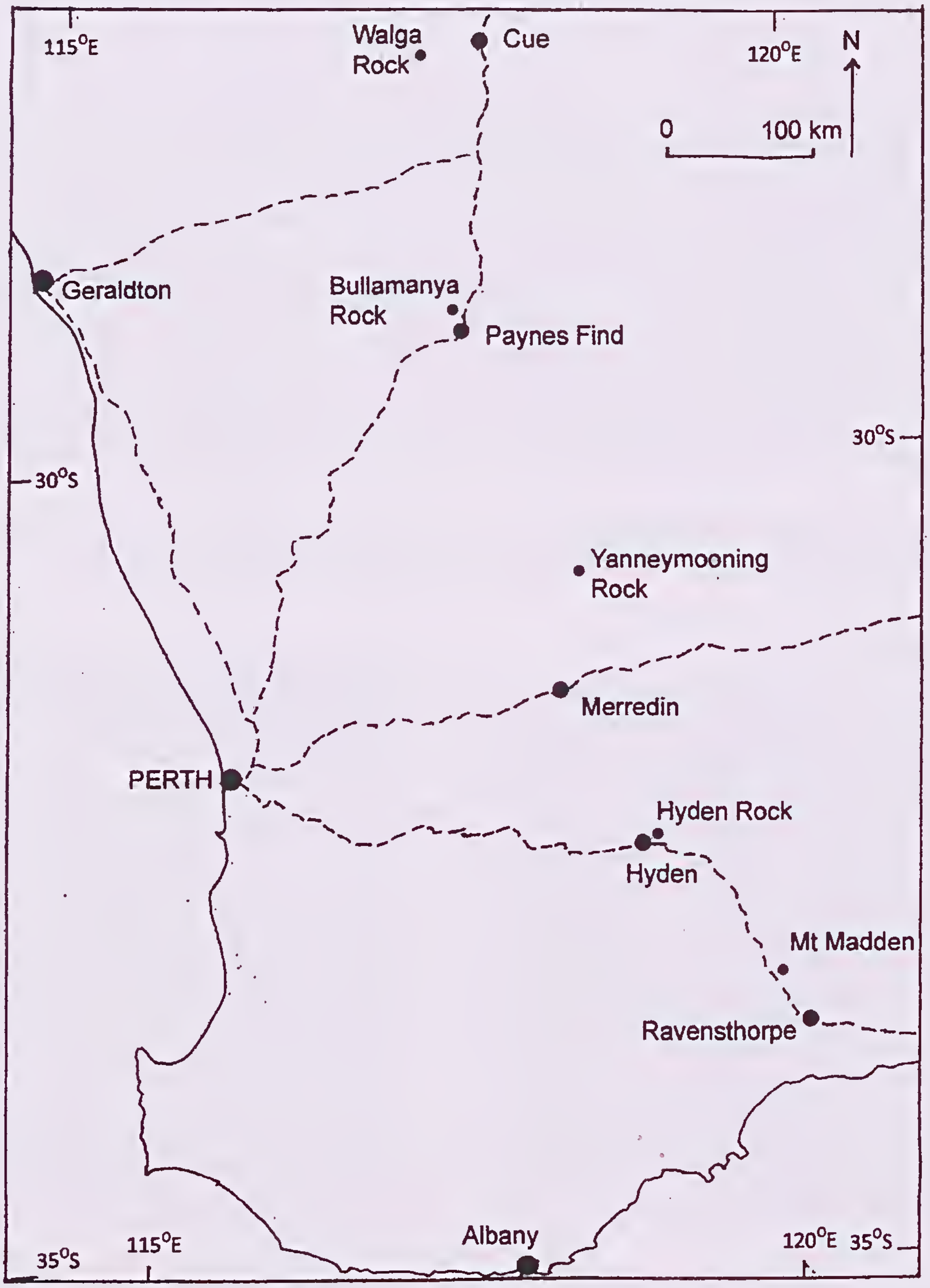


Figure 1. Map of southwestern Western Australia showing the location of the five rocks with reference to nearby locations.

each trip and was always conducted south to north. Overall the field work took 19 weeks and each rock was visited seven times almost synchronously (maximum 3–4 days apart). More frequent sampling would have been desirable, but sampling damages the pools physically and also conceptually could result in overharvesting (see below) from limited populations, but if this happened it was not noticed.

At each pool, water depth was determined with a stiff tape measure at the deepest point to the nearest 0.5 cm. Conductivity was measured with a Hanna HI8733 meter. There was no point is measuring water clarity as the pools were almost always crystal clear, nor water temperature as it varied widely diurnally. However, some seasonal highs and lows were noted, using an alcohol-in-glass thermometer accurate to ± 0.5 °C.

Two different nets were used to sample the fauna. A small plankton net, aperture 15 x 10 cm, 30 cm long and of mesh 159 µm, was used to sample microfauna in the water column and on the bottom surface (the latter by disturbing the sediment and then passing the net through the slurry). A household sieve, 20 cm in diameter and of mesh size ~2 mm was used for larger invertebrates. The number (5–20) of sweeps of each device was adjusted to pool size so that about 50% of the water volume in small pools was sampled down to 5% in the very large pools. This introduced an error between pools in estimating abundance and species richness, but the bias was constant between rocks and sampling dates. To have studied one pool size, if 10 pools per rock and 50 pools overall were exactly possible, would have introduced a greater misrepresentation in overall species richness per rock, given the variability between pools of different size (Vanschoenwinkel *et al.* 2009).

Plankton were concentrated by settling first in dilute ethanol, then pouring off supernatant and preserving in >70% ethanol. Sieve collections were handpicked in the field from a sorting tray; one individual (a few of more abundant chironomids) of each species was kept and preserved in 70% ethanol and the remainder returned alive to the pond. This protocol was adopted as there are many microinvertebrates with short life cycles in the pools so the loss of a few hundred every three weeks was thought to be insignificant, but to remove most of the few macroinvertebrates individuals on each sampling occasion would have considerably depleted populations. The numbers of sweeps to get representative samples were chosen based on a preliminary study the previous year. Even so, no matter how intense the sampling, and indeed the sampling of just 10 pools per rock, not all species present per pool/rock were necessarily caught (Jocqué *et al.* 2007a). Furthermore, though replicate sampling is desirable, it was not possible in smaller pools (due to unacceptable environmental damage and the sampling of a decreasing population) and was not employed in order to maintain a reasonably similar sampling regime across the pool spectrum. Sampling protocol was a compromise between damage to the pool, idealistic catching of all the fauna, and practical considerations of efficient time per unit effort.

In the laboratory each plankton collection for each pool was examined completely under an Olympus SZ61 stereomicroscope, species identified and the number of each species estimated on a log scale. The number of macroinvertebrates caught in the sieve was also estimated on a log scale. In a detailed study (B V Timms unpubl. data) of 96 pools on Anderson Rock (40 km north of Hyden Rock) distribution of invertebrates over the whole rock was heterogeneous and it depended on which 10 pools were sampled as to the perception of species richness and abundance for that rock outcrop. This problem is unsolvable unless all pools are sampled – species accumulation curves at Wave Rock continued rising even after 50 pools were sampled, albeit slowly after 10 pools (Jocqué *et al.* 2007a) but by sampling the same 10 pools each time on each rock, any bias was constant over the season.

Daily rainfall during 2010 was obtained from the Bureau of Meteorology website for weather stations as close as possible for each rock: for Mt Madden from Mt Madden 1.4 km southeast, for Hyden Rock from Hyden 3 km east, for Yanneymooning from Wattoning 34 km west, for Bullamanya Rock from Paynes Find 11 km south, and for Walga Rock from Cue 43 km east. Data are presented as monthly totals in Figure 2.

Relationships between assemblages on the five rocks were investigated using PRIMER (v5) (Clarke & Gorley 2001). Average seasonal abundance data of invertebrates from the mid-July, early and late August and mid-September trips (Table 1) was log (N+1) transformed prior to multivariate analysis. Non-metric multidimensional scaling, based on Bray–Curtis similarity index was used to represent assemblage composition in two-dimensional space. Relative distance apart in the ordination represents relative dissimilarity.

## RESULTS

### Pools

Unfortunately, 2010 was a drought year, so pools did not fill to their full capacity, nor for as long a period as usual. For the period April to October, Mt Madden rainfall was 56% of average, Hyden Rock 43%, Yanneymooning 25%, Bullamanya Rock 69% and Walga Rock 57% (Figure 2). Pools on Mt Madden (the southernmost rock) held water continuously from May to September but by early October most were dry (Figure 3). On Hyden Rock, pools were never as full and they started drying earlier, so that almost all were dry by early October. On Yanneymooning a few pools dried in August, but filled again in September, only for all to dry by early October. By contrast at Bullamanya Rock only one pool dried in August and half still had water in early October. Walga Rock's pools initially had some water, but dried completely in August and partially filled again in September to dry again by early October (Figure 3). Pools with water on the three southern rocks were of maximum number and cumulative depth in mid July, while Walga Rock's pools were maximal in mid-September. Bullamanya's pools were intermediate between these two extremes (Figure 3).

During winter, the minimum water temperature measured during daylight was 3.0°C (on 22 July at Hyden Rock). The maximum water temperature observed was 26.4°C at Bullamanya Rock on 6 October. While almost all pools contained crystal-clear water and hence their floors were clearly visible, occasionally a few

**Table 1** Species occurrences on the five rocks

| Major group | Species | Madden | | Hyden | | Yanney | | Bullam | | Walga | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2009 | 2010 | 2009 | 2010 | 2009 | 2010 | 2009 | 2010 | 2009 | 2010 |
| Turbellaria | unidentified black planarian | o | x | o | x | o | x | o | x | - | - |
| | unidentified green planarian | o | xxxx | o | xx | o | r | - | x | - | - |
| | unidentified rhabdocoel | - | r | - | r | - | - | - | - | - | - |
| Nematoda | unidentified nematodes | o | x | o | xx | o | r | o | - | o | x |
| Branchiopoda | *Branchinella longirostris* | - | x | - | r | o | xx | o | xxx | o | x |
| | *Limnadia badia* | o | xxx | o | x | o | xx | o | xxx | - | - |
| | *Caenestheriella mariae* | - | - | - | - | - | r | o | xx | o | x |
| | *Triops* n. sp. | - | - | - | - | - | - | - | r | o | x |
| | *Daphnia jollyi* | - | - | o | - | o | r | o | r | - | - |
| | *Ceriodaphnia* sp. | o | xxxx | o | xxx | - | - | - | - | - | - |
| | *Moina australiensis* | - | x | - | r | o | - | - | - | - | - |
| | *Ilyocryptus* sp. | o | r | - | - | - | - | - | - | - | - |
| | *Macrothrix hardingi* | - | r | o | - | - | xx | - | xxx | - | - |
| | *Macrothrix* spp. | o | xxx | o | x | - | r | - | x | - | - |
| | *Neothrix* spp. | o | r | o | x | o | x | - | xx | - | - |
| | *Alona macrocopa* | o | r | - | r | - | r | - | - | - | - |
| | *Alona rigidicaudis* | o | r | o | - | - | - | - | - | o | - |
| | *Alona* spp. | - | r | - | r | - | - | - | - | - | - |
| | *Chydorus hybridus* | o | r | - | r | - | - | o | - | - | - |
| | *Ephemeroporus tridentata* | o | xxx | - | x | - | r | - | x | - | - |
| | *Leberis aenigmatosa* | - | r | o | xx | o | xx | - | r | - | - |
| | *Monospilus diporus* | - | - | o | r | - | - | - | - | - | - |
| | *Planicirculus alticarinatus* | o | xxx | o | r | o | r | o | - | - | - |
| | *Plurispina multituberculata* | o | xxx | o | xx | o | r | - | r | - | - |
| | *Rak* sp | o | x | o | r | - | - | - | - | - | - |
| Copepoda | *Boeckella opaqua* | o | xxxx | o | xxx | o | xxx | o | xxxx | - | x |
| | *Metacyclops laurentiisae* | o | x | - | - | - | - | - | - | - | - |
| | harpacticoid Sp 674 (SAP) | - | r | - | - | - | - | - | - | - | - |
| Ostracoda | *Bennelongia* sp 563. | o | xxx | o | x | - | r | o | x | o | r |
| | *Candonocypris* spp. | - | x | - | x | - | r | - | r | - | - |
| | *Cypretta baylyi* | - | x | o | x | o | r | o | x | - | - |
| | *Cypricercus* sp 637 | o | xxxx | o | xxx | - | xxx | o | xxx | o | - |
| | *Cypricercus* spp. | - | r | - | - | - | - | - | - | - | |
| | *Ilyodromus amplicolis* | o | xxx | o | xxx | o | x | o | xx | o | R |
| | *Ilyodromus* sp. 630 | - | r | - | r | - | r | - | - | - | - |
| | *Ilyodromus* spp.. | - | r | - | - | - | - | - | - | - | - |
| | *Limnocythera porphyetica* | o | r | o | r | o | - | o | r | - | - |
| | *Sarscypriodopsis* spp.. | o | xxx | o | xxx | o | - | o | - | - | - |
| Odonata | *Hemicordulia tau* | - | r | - | - | o | r | - | x | - | - |
| Hemiptera | *Micronecta* sp. | o | r | o | r | o | x | - | - | - | r |
| | *Agraptocorixa* spp. | o | r | o | r | - | r | - | - | o | r |
| | *Anisops gratus* | - | - | o | r | - | r | o | r | - | - |
| | *Anisops hyperion* | o | r | - | - | - | - | - | - | - | - |
| | *Aniops thienemanni* | o | r | o | r | - | r | - | - | - | - |
| Coleoptera | *Allodessus bistrigatus* | o | r | o | r | - | r | o | - | o | - |
| | *Antiporus gilberti* | o | r | o | r | - | - | - | r | - | - |
| | *Berosus* sp | - | - | o | r | - | - | - | r | - | r |
| | *Eretes australis* | - | - | - | r | - | r | - | r | - | r |
| | *Halochares* sp. | - | - | - | r | - | - | - | - | - | - |
| | *Hyphydrus elegans* | o | - | - | - | - | - | - | - | - | - |
| | *Hydrovatus* sp. | - | - | - | - | - | - | - | r | - | - |
| | *Limnoxenus novaezealandiae* | - | r | - | - | - | - | - | - | - | - |
| | *Lancetes lanceolatus* | - | r | - | r | - | - | - | - | - | - |
| | *Megaporus howetti* | - | r | - | - | - | - | - | - | - | - |
| | *Necterosoma* sp. | - | - | - | - | - | - | - | - | - | r |
| | *Paroster* nr *michaelseni* | - | r | - | r | - | x | - | r | - | r |
| | *Rhantus suturalis* | - | - | - | r | - | - | o | r | - | - |
| | *Sternopriscus multimaculatus* | o | r | o | r | o | r | o | - | o | r |
| | unidentified curculionid | - | - | - | - | - | r | o | - | - | - |
| | *Allodessus* larvae | o | - | o | - | o | - | o | - | o | - |
| | *Antiporus* larvae | o | r | o | r | - | - | - | r | o | - |
| | *Berosus* larvae | - | - | - | - | - | - | - | - | o | - |
| | *Enochrus* larvae | o | - | - | - | - | - | - | - | - | - |
| | *Lancetes* larvae | - | r | - | r | - | r | - | - | - | - |
| | *Limnoxenus* larvae | - | - | o | - | - | - | - | - | - | - |
| | *Paroster* larvae | - | r | - | r | o | x | o | x | - | r |
| | *Sternopriscus* larvae | o | - | o | - | o | - | o | - | o | - |

Table 1 (cont.)

| Major group | Species | Madden | | Hyden | | Yanney | | Bullam | | Walga | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2009 | 2010 | 2009 | 2010 | 2009 | 2010 | 2009 | 2010 | 2009 | 2010 |
| Diptera | juvenile chironomids | o | x | o | r | o | x | o | x | - | - |
| | *Allotrissocladius* sp. L | o | r | o | r | o | x | o | x | o | - |
| | *Chironomus tepperi* | - | - | o | - | - | x | - | xx | - | - |
| | *Paraborniella tonnoiri* | o | r | o | x | o | x | o | x | o | xxx |
| | *Parakeifferiella variagatus* | - | - | - | r | - | r | - | r | - | - |
| | *Procladius* sp. | o | r | - | x | - | x | o | x | - | - |
| | *Tanytarsus* sp. | - | - | - | - | - | - | - | - | - | - |
| | *Dasyhelia* sp. | o | r | o | x | o | r | o | x | - | x |
| | *Aedes alboannulatus* | - | r | - | r | - | r | - | - | - | - |
| | *Culex starkeae* | - | - | - | - | - | - | - | r | - | - |
| | stratiomyid larvae | - | - | - | r | - | - | - | - | - | - |
| | tabanid larvae | - | - | - | - | - | r | - | - | - | - |
| Arachnida | hydrocarinid mites | - | - | - | - | o | - | o | - | - | - |
| | trombidioid mites | - | - | - | - | - | r | - | r | - | - |
| | orbatid mites | o | - | o | - | - | - | - | - | - | - |
| Mollusca | *Glyptophysa* sp. | o | xxx | - | - | - | - | - | - | - | - |
| | Total | 37 | 51 | 36 | 41 | 25 | 41 | 26 | 37 | 16 | 17 |
| | Grand total (2009 + 2010) | 54 | | 47 | | 45 | | 45 | | 23 | |
| | Mean MSR peak period | 30.75 | | 26.5 | | 29.5 | | 26.5 | | 10.6 | |

Presence in 2009 noted by an 'o' and abundances in 2010 given variously by 'r' for rare up to 'xxxx' for various degrees of abundance. Abundances are averages over the four plateau samples (July to Sept). For totals of species, juveniles are only counted if no adults in that genus have been recorded.

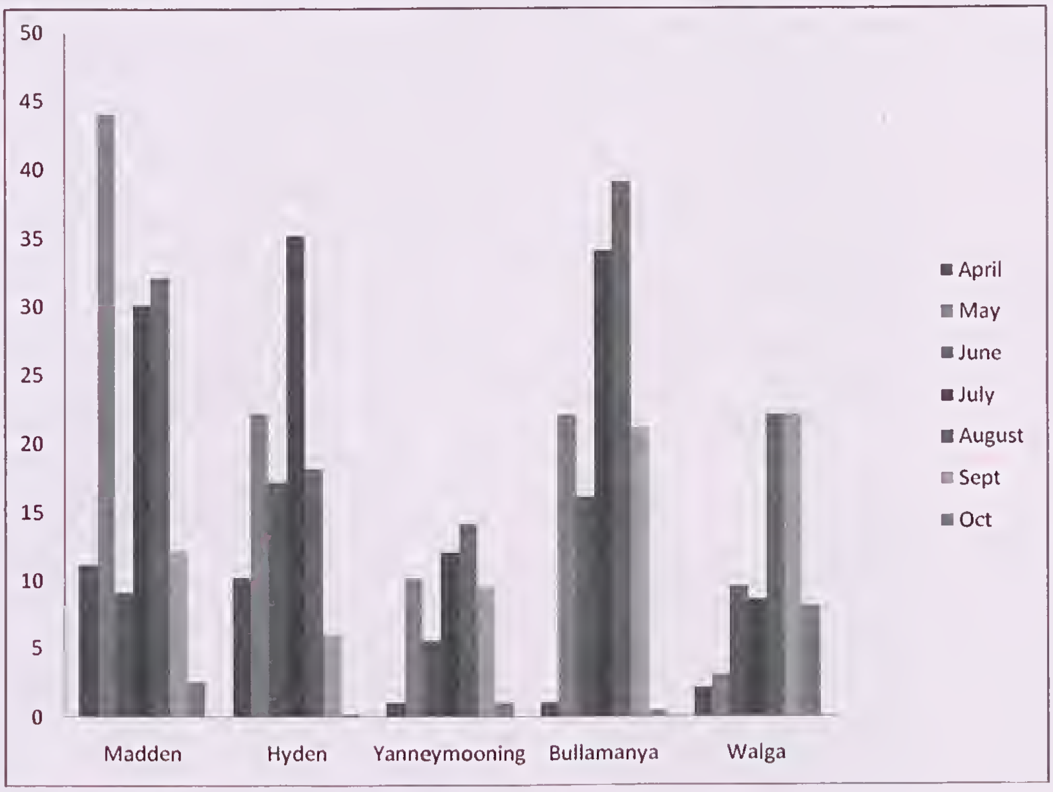


**Figure 2.** Monthly rainfall in millimetres at each of the five sites during 2010

pools had cloudy water with Secchi disc values less than their depths (i.e. at 10–20 cm, but still not particularly turbid) Conductivities varied between 45 and 1300 µS/cm, with values typically increasing as pools dried. Some pools contained abundant filamentous algae and most southern pools (particularly on Mt Madden and Hyden and to some degree on Yanneymooning) had a floor of aquatic plants, mainly of *Isoetes* sp. and *Glossostigma* sp.

### Species richness

Seventy-two invertebrate taxa were identified in this group of gnammas (Tables 1, 2). In that some taxa represented more than one species [as indicated in the species lists (Table 1)], the total number of species present was probably about 5–10% more than this. Cumulative species richness per rock (over the entire study) decreased from south to north, with the decline steeper

**Table 2** Number of pools of the 10 studied on each rock with each species

| Major group | Species | Madden | Hyden | Yanney | Bullen | Walga |
|---|---|---|---|---|---|---|
| Turbellaria | unidentified black planarian | 7 | 9 | 8 | 9 | - |
| | unidentified green planarian | 10 | 4 | 1 | 2 | - |
| | unidentified rhabdocoel | 1 | 1 | - | - | - |
| Nematoda | unidentified nematodes | 5 | 8 | 7 | - | 4 |
| Branchiopoda | *Branchinella longirostris* | 4 | 2 | 8 | 9 | 6 |
| | *Limnadia badia* | 6 | 8 | 6 | 10 | - |
| | *Caenestheriella mariae* | - | - | 2 | 5 | 8 |
| | *Triops* n. sp | - | - | - | 2 | 4 |
| | *Daphnia jollyi* | - | - | 1 | 1 | - |
| | *Ceriodaphnia* sp. | 10 | 10 | - | - | - |
| | *Moina australiensis* | 2 | 2 | - | - | - |
| | *Ilyocryptus* sp. | 1 | - | - | - | - |
| | *Macrothrix hardingi* | 1 | - | 4 | 6 | - |
| | *Macrothrix* spp. | 7 | 3 | 1 | 2 | - |
| | *Neothrix* spp. | 1 | 4 | 3 | 7 | - |
| | *Alona macrocopa* | 1 | 2 | 1 | - | - |
| | *Alona rigidicaudis* | 1 | - | - | - | - |
| | *Alona* spp. | 2 | 1 | - | - | - |
| | *Chydorus hybridus* | 1 | 1 | - | - | - |
| | *Ephemeroporus tridentata* | 5 | 2 | 1 | 4 | - |
| | *Leberis aenigmatosa* | 3 | 6 | 4 | 2 | - |
| | *Monospilus diporus* | - | 1 | - | - | - |
| | *Planicirculus alticarinatus* | 8 | 3 | 2 | - | - |
| | *Plurispina multituberculata* | 7 | 7 | 2 | 2 | - |
| | *Rak* sp | 3 | 1 | - | - | - |
| Copepoda | *Boeckella opaqua* | 10 | 10 | 10 | 10 | 8 |
| | *Metacyclops laurentiisae* | 4 | - | - | - | - |
| | harpacticoid Sp 674 (SAP) | 1 | - | - | - | - |
| Ostracoda | *Bennelongia* sp 563. | 9 | 5 | 2 | 5 | 4 |
| | *Candonocypris* spp. | 4 | 5 | 3 | 5 | - |
| | *Cypretta baylyi* | 3 | 4 | 1 | 4 | - |
| | *Cypricercus* sp 637 | 9 | 10 | 9 | 10 | - |
| | *Cypricercus* spp. | 1 | - | - | - | - |
| | *Ilyodromus amplicolis* | 8 | 9 | 5 | 9 | 3 |
| | *Ilyodromus* sp. 630 | 1 | 1 | 1 | - | - |
| | *Ilyodromus* spp. | 1 | - | - | - | - |
| | *Limnocytheria porphyetica* | 2 | 2 | - | 1 | - |
| | *Sarscypriodopsis* spp.. | 7 | 8 | - | - | - |
| Odonata | *Hemicordulia tau* | 2 | - | 2 | 3 | |
| Hemiptera | *Micronecta* sp. | 4 | 5 | 5 | - | 2 |
| | *Agraptocorixa* spp. | 3 | 3 | 2 | - | 1 |
| | *Anisops gratus* | - | 2 | 3 | 3 | - |
| | *Anisops hyperion* | 2 | - | - | - | - |
| | *Aniops thienemanni* | 5 | 5 | 4 | - | - |
| Coleoptera | *Allodessus bistrigatus* | 7 | 3 | 3 | - | - |
| | *Antiporus gilberti* | 2 | 3 | - | 2 | - |
| | *Berosus* sp | - | 2 | - | 2 | 3 |
| | *Eretes australis* | - | 2 | 3 | 3 | 2 |
| | *Halochares* sp. | - | 2 | - | - | - |
| | *Hydrovatus* sp. | - | - | - | 2 | - |
| | *Limnoxenus novaezealandiae* | 2 | - | - | - | - |
| | *Lancetes lanceolatus* | 1 | 1 | - | - | - |
| | *Megaporus howetti* | 2 | - | - | - | - |
| | *Necterosoma* sp. | - | - | - | - | 1 |
| | *Paroster* nr *michaelseni* | 4 | 5 | 7 | 5 | 2 |
| | *Rhantus suturalis* | - | 2 | - | 1 | - |
| | *Sternopriscus multimaculatus* | 5 | 4 | 3 | - | 2 |
| | unidentified curculionid | - | - | 1 | - | - |
| | *Antiporus* larvae | 3 | 2 | - | 1 | - |
| | *Lancetes* larvae | 1 | 1 | 1 | - | - |
| | *Paroster* larvae | 4 | 4 | 7 | 5 | 2 |
| | *Sternopriscus* larvae | - | - | - | - | - |
| Diptera | juvenile chironomids | 7 | 6 | 8 | 5 | - |
| | *Allotrissocladius* sp. L | 4 | 2 | 6 | 5 | - |
| | *Chironomus tepperi* | - | - | 5 | 5 | - |
| | *Paraborniella tonnoiri* | 2 | 6 | 6 | 7 | 9 |
| | *Procladius* sp. | 2 | 3 | 4 | 3 | - |
| | *Dasyhelia* sp. | 4 | 6 | 3 | 5 | 5 |
| | *Aedes alboannulatus* | 1 | 3 | 1 | - | - |
| | *Culex starkeae* | - | - | - | 1 | - |
| Arachnida | trombidioid mites | - | - | 3 | 2 | - |

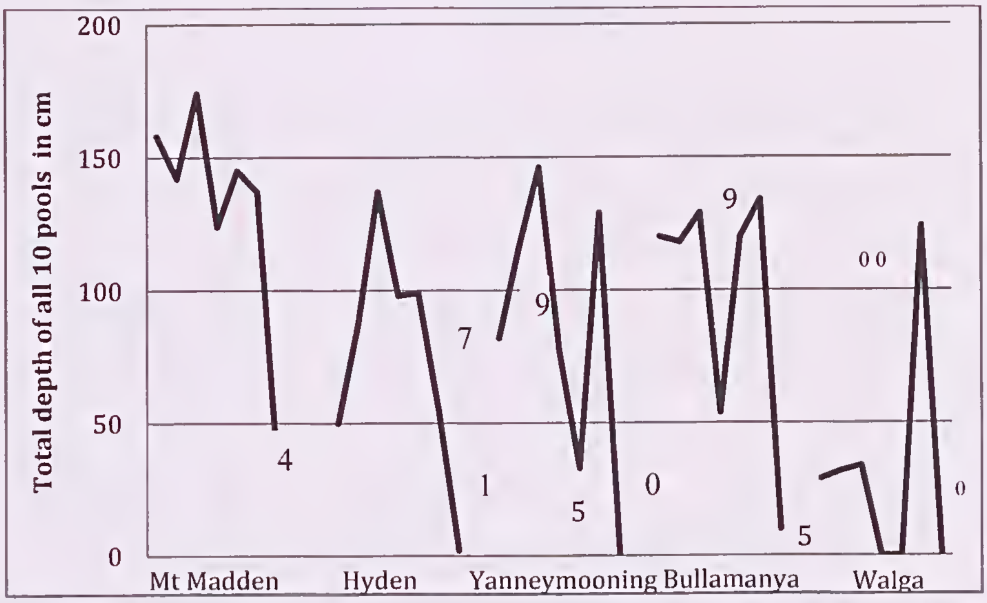


**Figure 3.** Total depth of all 10 pools on the five rocks over the seven samplings (May to October). Number of pools holding water was usually 10 per rock, except where indicated.

towards the north: Mt Madden had 51 taxa, Hyden 41, Yanneymooning 41, Bullamanya 37 and Walga 17. Species richness was greater in 2010 than in the preliminary 2009 survey because the more thorough sampling in 2010 netted many uncommon species (Tables 1, 2). Species richness for each set of 10 pools varied between trips and was usually minimal in early and late trips, peaking for the middle trips. Early visits missed late hatching and late colonising species whereas late visits lost quicker drying pools and their fauna. Mean momentary species richness per rock hardly decreased south to north except for Walga Rock, and plateaued in July to September (from 9–18 weeks after filling): Mt Madden 30.75 ± 0.96 species, Walga 26.5 ± 4.1, Yanneymooning 29.5 ± 3.0, Bullamanya 26.5 ± 4.4, Walga 10.6 ± 2.1. Mt Madden's plateau continued longer and species richness hardly varied in keeping with its pools being more stable hydrologically (Appendix 1).

Differences between southern and northern sites were characterised by a decrease in certain taxa in the two northern sites, notably the absence and reduced presence of cladocerans at Walga and Bullamanya, respectively, compared to up to 15 species at southern sites. Walga was also characterised by the absence of planarians and fewer ostracods, hemipterans and beetles.. On the other hand, Mt Madden had some taxa not seen on other rocks, notably a cyclopoid and harpacticoid copepod, a snail and extra insects. Counter to this pattern was the presence of two large branchiopods (*Caenestheriella mariae* and *Triops* n. sp.) only at the northern rocks and of *Daphnia jollyi* and hydrocarinid and trombidioid mites at Yanneymooning and Bullamanya. In the latter two rocks *Macrothrix hardingi* replaced *Ceriodaphnia* n. sp. as the most common cladoceran. However all sites, except Walga, shared most of the species encountered.

Relative dominance of the most abundant species (Figures 4–9) showed *Boeckella opaqua* to be the most abundant species on average at four of the five sites and present at the fifth. The next most widespread and abundant species was *Cypricercus* sp. 637, followed by a large group abundant on a few rocks, but not present on all. These include *Ceriodaphnia* sp. and green planarians (southern rocks), *Branchinella longirostris, Limnadia badia, Neothrix armata* and black planarian (middle rocks) and *Paraborniella tonnoiri* and *Caenestheriella mariae* (northern rocks). An alternative view of relative dominance is gained by analysing the number of pools on each rock containing each species (Table 2). Overall this confirmed the common and rare species, but in general uncommon insects occurred in more pools than uncommon crustaceans. The ordination diagram from a multivariate analysis (Figure 10) showed a relationship best explained by factors associated with latitude, though the separation between Yanneymooning and Bullamanya was slight. Mt Madden in the far south and Walga Rock in the far north were the most variant, probably due to the dominance of some extra species at Mt Madden and the restricted species richness at Walga Rock.

### Phenology

There was little sequential appearance of species during the aquatic stage of the gnammas; most species peaked according to their speed of development (Figures 4–9, Appendix 1). Southern pools had a earlier start in broad agreement with filling associated with rainfall—Mt Madden with 11 mm in April was the most advanced when sampled commenced in late May, and Bullamanya the least advanced with only 0.8 mm in April. Differences in speed of community development soon faded on subsequent sampling trips, except at Walga which exhibited a stop-start pattern associated with its erratic hydroperiods.

Branchiopod larvae and chironomids (mainly *Paraborniella tonnoiri*) appeared first in all gnammas on all rocks (Figures 4–9). *Paraborniella tonnoiri* were fourth instars that had been in suspended animation (Jones 1971). Following reactivation they soon pupated and adults emerged and dispersed, so larval numbers dropped rapidly. This pattern was very different to that of *Chironomus tepperi* which colonised some ponds from

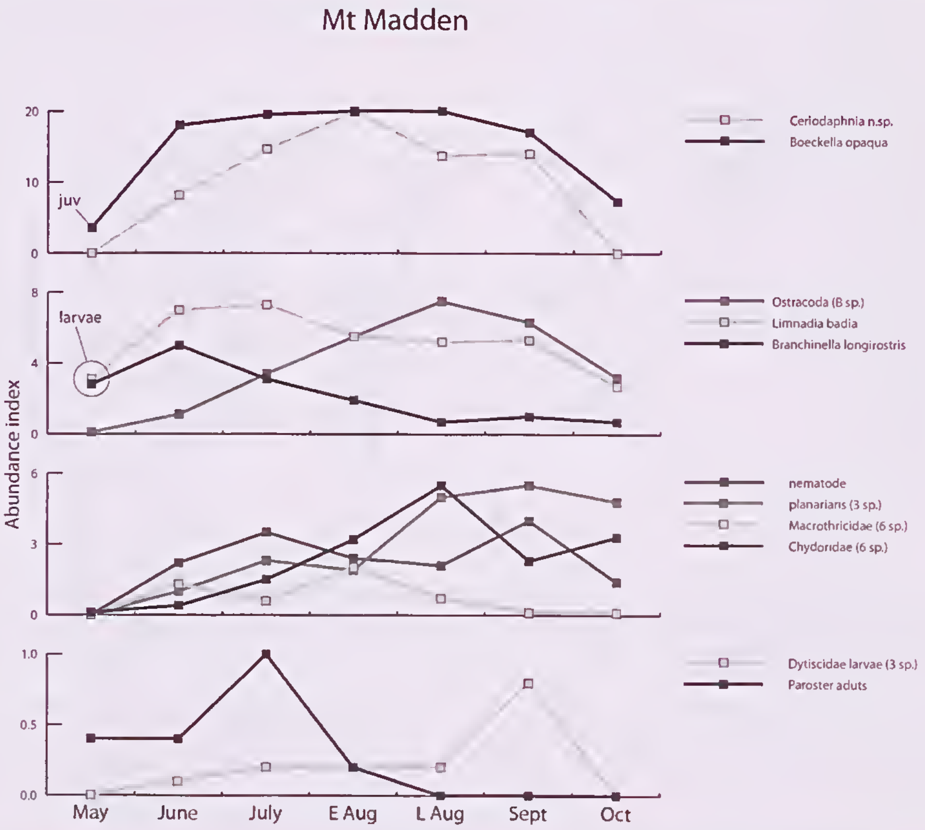


**Figure 4.** Seasonal changes in 11 taxa/taxonomic groups on Mt Madden. Abundance indices in Figures 4–9 are calculated by adding all abundance values for all pools, and hence show the relative success of a taxon on a rock, as measured by its pooled abundances in the 10 study gnammas. Circles on the figures indicate abundances were due to larvae.

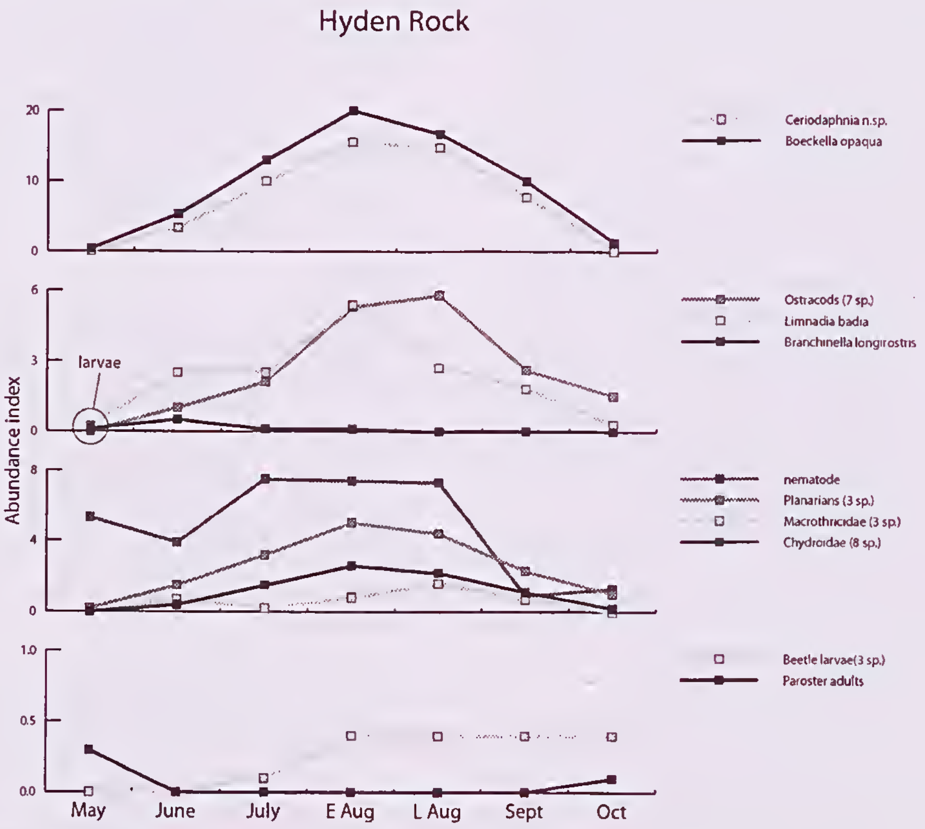


**Figure 5.** Seasonal changes in the same 11 taxa/taxonomic groups in the same order on Hyden Rock

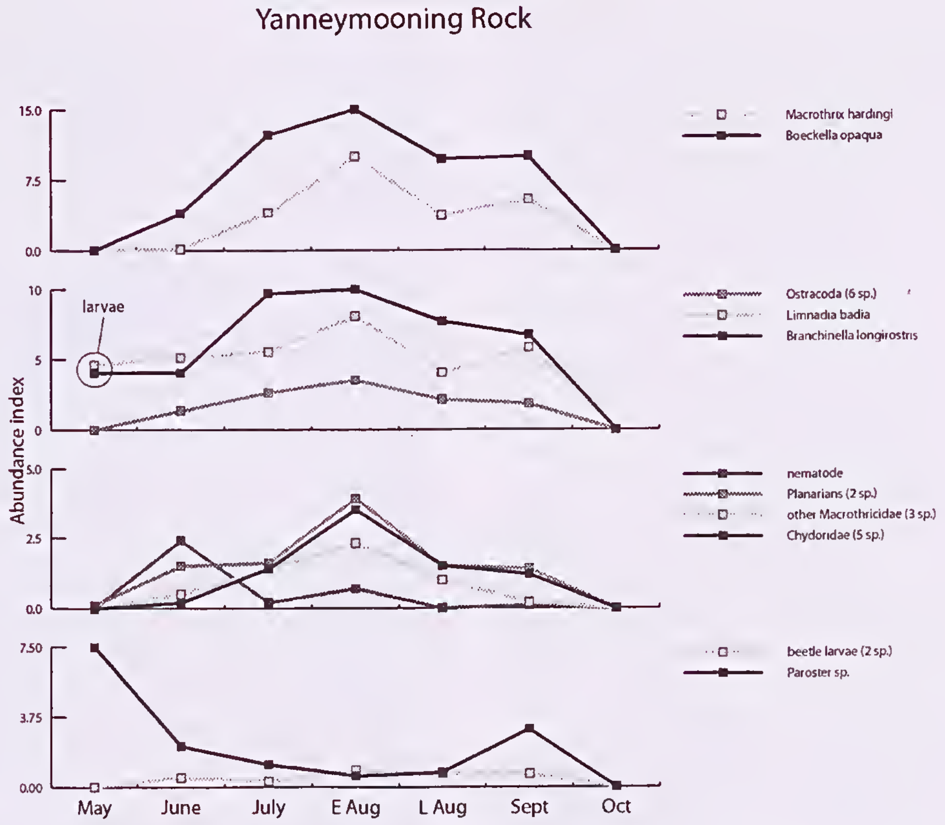


**Figure 6.** Seasonal changes in the same 11 taxa/taxonomic groups (with *Macrothrix hardingi* substituted for *Ceriodaphnia* n .sp.) in the same order on Yanneymooning Rock.

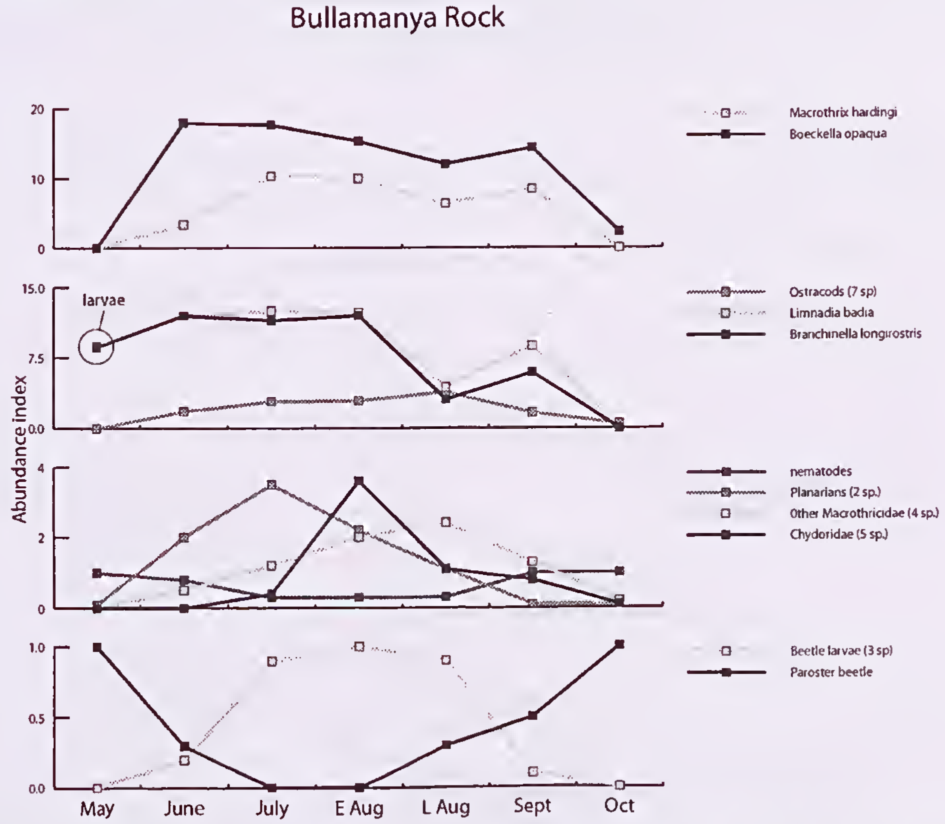


**Figure 7.** Seasonal changes in the same 11 taxa/taxonomic groups (as on Yanneymooning Rock) in the same order on Bullamanya Rock.

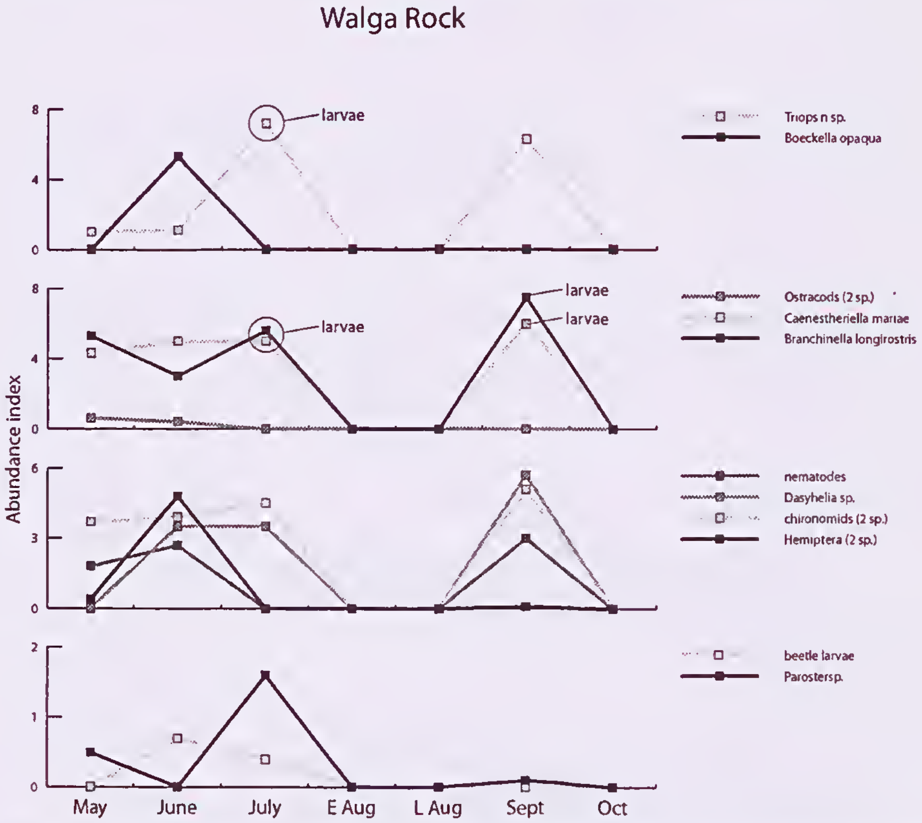


**Figure 8.** Seasonal changes in 11 common taxa/taxonomic groups on Walga Rock (these are not comparable with those on the other four rocks).

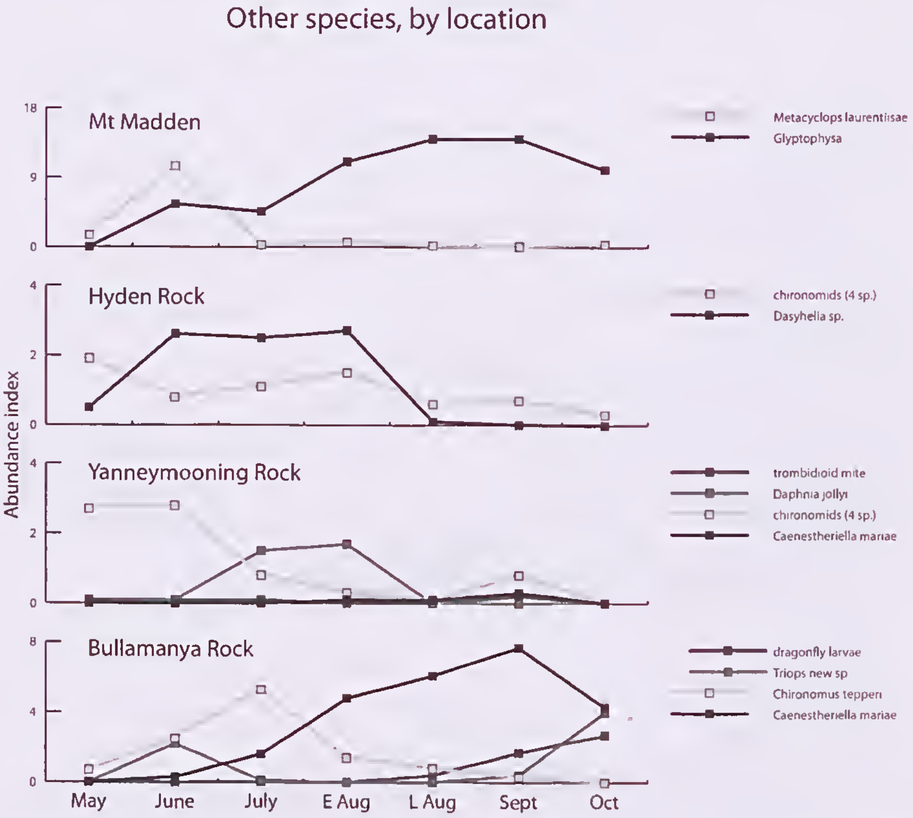


**Figure 9.** Seasonal changes in some other common species that are largely restricted to, or most common on, particular rocks.

semipermanent waters nearby (as at Bullamanya Rock) so that its numbers peaked in week 6 (Figure 9). Another early starter in Mt Madden was the cyclopoid *Metacyclops laurentiisae* which appeared early on as adults and then increased rapidly by the next visit in June before falling to low numbers through the remainder of the hydroperiod (Figure 9). The branchiopods, *Branchinella longirostris* and *Limnadia badia* matured early and were most common over the next 3–9 weeks, waning in the last 6–9 weeks (Figures 4–7), though *L. badia* often persisted until pools dried. *Triops* n. sp. was also a quick developer and hatched repeatedly if the pools dried and re-wetted (as at Walga and Bullanmanya Rocks) (Figures 8, 9). They occurred almost exclusively in pools with flat rocks and usually were found hiding under these rocks. On the other hand the clam shrimp *Caenestheriella mariae* developed somewhat slower reaching a peak in the middle or late life of pools (Figures 8, 9). All of the branchiopods were univoltine.

Less prominent early starters were the planarians (Figures 4–7) peaking 6–12 weeks after filling, with the black planarian developing quicker than the green species and waning earlier; it was also the most widespread planarian while the rhabdocoel was restricted in distribution to the south and limited in abundance. Nematodes were most common in southern rock pools and peaked variously at 6–18 weeks (Figures 4–8).

Some insects invaded the southern rocks early on; the most prominent of these was the beetle *Paroster*, particularly on Yanneymooning where it peaked very early and again as pools dried (Figures 4–8). Larvae appeared 3–6 weeks into the hydroperiod and were small but by 12–15 weeks were relatively large and in declining numbers as the pools dried at 15–18 weeks. Other beetles, mainly *Sternopriscus multimaculatus* and *Eretes australis*, also successfully bred in many of the pools, mainly in the south. An insect which failed to breed successfully in the short hydroperiod of 2010 was the odonatan *Hemicordulia tau*. On Bullamanya (Figure 9), large numbers of immature larvae died in early October in some pools, while elsewhere only a few immature individuals died; in all cases there was no evidence that any matured and emerged. Of the few hemipterans visiting the pools, *Micronecta* sp. was the most common followed by *Anisops thienemanni*. Most hemipterans bred, and while some matured before the pools dried prematurely, many did not in 2010.

*Boeckella opaqua*, the most common invertebrate of most pools, variously peaked at 3–9 weeks (Figures 4–8). It had a few overlapping generations, and hence was multivoltine. The other abundant open-water plankters included *Ceriodaphnia* n. sp., *Macrothrix hardingi* and occasionally *Daphnia jollyi*, which all tended to peak in the 12th week (Figures 4–9), i.e. after the open-water branchiopods, and all three were multivoltine with overlapping generations. There were many benthic cladocerans peaking at various times with little overall pattern, though the majority of the abundant ones also peaked in the 12th week (Figures 4–7). Again the presence of numerous juveniles of most species during the season suggest most are multivoltine. All had ephippial eggs as the pools shrunk and dried. Ostracods tended to peak a little later than cladocerans, in the 12–15th weeks (Figures 4–7). It was not uncommon for them to persist longer than other crustaceans and dried remains in pools often featured shells of *Ilyodromus* and *Bennelongia*, as well as those of *Limandia badia*. Once mature, the larger ostracods such as *Bennelongia*, *Cypretta* and *Ilyodromus* did not vary in size so were probably univoltine. No data were collected on the smaller taxa such as *Cypricercus*.

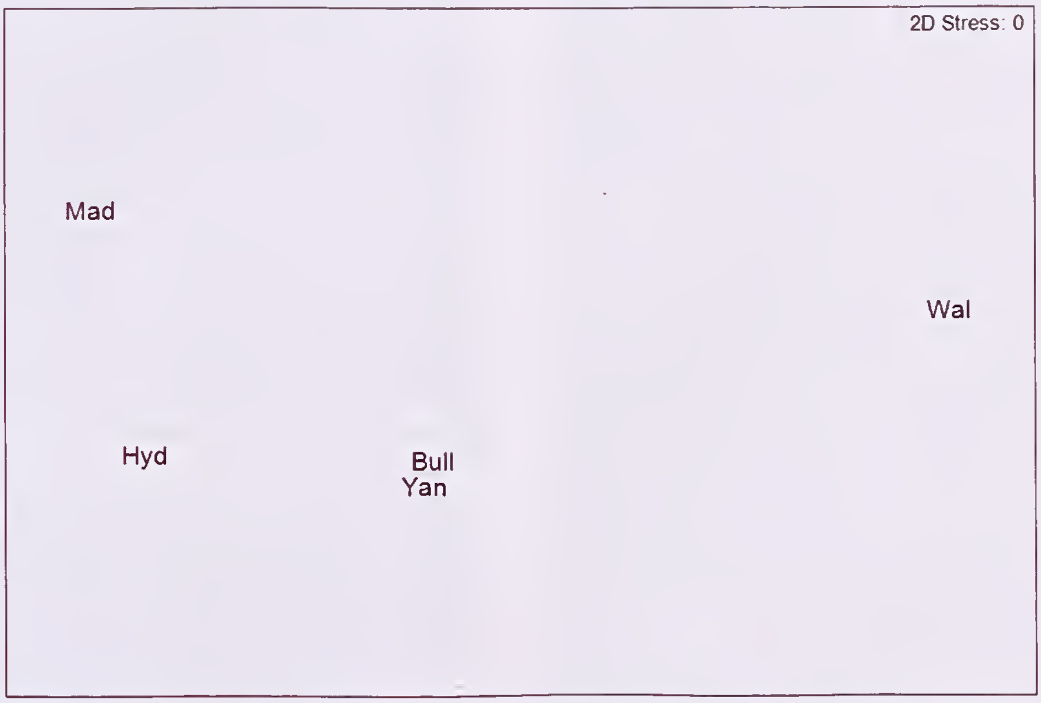


**Figure 10.** Ordination diagram of the relative dissimilarity of the invertebrate assemblages on the five rocks.

Few dipteran larvae were recorded except for some chironomids. Mosquitoes were particularly uncommon as were various larvae such as stratomyids and tabanids. Ceratopogonids were common in some pools on some rocks; those in Mt Madden and Yanneymooning peaked late (12–15 weeks), while those on Hyden Rock peaked early (3–9 weeks) then suddenly waned.

Only Mt Madden had the snail *Glypophysa*. It appeared early as adults, bred and then numbers peaked at 9–12 weeks (Figure 9). As the pools dried, populations disappeared to under rocks on mud where adults and maturing juveniles began aestivating. At this stage they were easily activated again by immersing in water. Numbers under rocks did not match the large numbers seen in pools during the height of the season.

Few mites were recorded but included terrestrial trombidioid mites. These persisted for a few weeks after filling in Yanneymooning and Bullamanya Rocks and at Yanneymooning they were back again as the pools dried (Figure 9). During the dry season, at least in the October visit and on an extra November visit to Yanneymooning, they could be found under rocks and amongst coarse gravel.

## DISCUSSION

Species richness and composition amongst temporary pools, even within sites is highly variable (Pinder *et al.* 2000; Jocqué *et al.* 2007b) so that authors prefer to make species lists for districts or whole rocks rather than for individual or small groups of pools (Bayly 1982, 1997; Pinder *et al.* 2000; Jocqué *et al.* 2007a). Considering district totals, the 72 species recorded from this study compares with 88 species from just 36 gnammas on 17 different granite outcrops across the wheatbelt (Bayly 1997). The more wide ranging and detailed study of Pinder *et al.* (2000) recorded 230 species across a much wider area of southwestern Western Australia (but only from nine rocks and an unspecified number of pools). Clearly, district cumulative species richness (CSR) depends on the size of the district so that it is more instructive to consider CSR on individual outcrops. For the Western Australian Wheatbelt CSR per rock outcrop is around 45–60 species; Pinder *et al.* (2000) quoted 49 ±15 in their study, Jocque *et al.* (2007a) listed 58 taxa for Hyden (Wave) Rock and 43 taxa for King Rocks, and the present study recorded 47 species on Hyden Rock, and between 22 and 54 species for the other four rocks. These figures well exceed the <20 CSR for rockpools in other parts of the world (Jocqué *et al.* 2010) and in eastern Australia (Bishop 1974; B V Timms unpubl. data). The number of species per pool during the period of maximum diversity is around 25–30 (except on Walga Rock), which is higher than figures given by other authors: for example Bayly (1997) listed 7–15 species for pools on Mt Madden. Discrepancies could be due to different sampling techniques, sampling at different stages in the hydrologic cycle and taxonomic expertise. Also there could be differences between years, though the data from the study rocks (Table 1) suggests a similar composition in 2009 and 2010 except for numerous uncommon species encountered in 2010 with greater sampling effort. The significantly lower diversity in the north clearly was associated with its shorter and unreliable hydroperiods on the phenology of some species, as experienced during 2010 on Walga Rock (Vanschoenwinkel *et al.* 2009, 2010). The same factor operated to a much lesser degree on the next rock to the south, Bullamanya, where at least *Hemicodulia tau* failed to complete its life cycle in 2010.

Despite the high variability in species richness and species composition on and between rocks, it seems there may be a pattern across the southwest of Western Australia. Compared to gnammas in the central Wheatbelt, the pools in the forested west and southwest corner of Western Australia studied by Bayly (1982) have a reduced fauna of 35 species overall, with fewer species in most groups, particularly turbellarians and beetles. Similarly gnammas well north of the Wheatbelt, such as Walga Rock have fewer species, again in most groups, but most noticeably among cladocerans, tubellarians and beetles. In both cases dominants are largely similar to those in the central Wheatbelt. There is also a decrease in species richness from south to north as seen in the present study and the more detailed assessment by Jocqué (2007) and Jocqué *et al.* (unpubl. data). These differences, and maybe there are also changes east to west (B V Timms unpubl. data), must be associated with major climatic differences though habitat parameters may also be influencial (Vanschoenwinkel *et al.* 2009). Central is the reliability of rainfall and lengths of hydroperiod, as well as perhaps temperature and evaporation potential differences, between the central Wheatbelt and fringe areas. Rainfall gradients are from the southwest to the northeast, so not quite concordant with the axis of the study rocks, whereas temperature gradient and evaporation potential are more south–north oriented. There could also be a difference in food sources. Bayly (1982) mentioned the importance of organic matter input from decaying mosses and lichens in the Northcliffe pools and recorded few plants in these pools. By contrast in central Wheatbelt gnammas, organic matter derived from mosses and lichens does not seem so important, and the influence of vegetation, particularly of *Isoetes* and *Glossostigma*, stronger on features such as habitat complexity and possibly on periphyton availability. Northern sites such as Walga Rock lack vegetation (and hence the microcrustaceans associated with this habitat) and as seen in 2010 can have reduced hydroperiods preventing completion of life cycles.

Salinity is an important environmental control in many Australian waters (Pinder *et al.* 2002 for southwestern Australia) and in some temporary waters (Waterkeyn *et al.* 2008), but not in gnammas. The study gnammas contained waters of low to very low total dissolved salts and they remained fresh throughout the hydroperiod. Salinity thresholds for Australian inland aquatic fauna are higher by at least an order of magnitude (Hart *et al.* 1991), so this factor was dismissed as inapplicable in this study.

Habitat structure is important for the presence of some species. On both Bullamanya and Walga Rocks, *Triops* n. sp. occurred only in pools with flat rocks standing off the bottom, probably as such arrangements provided refuges against predation from birds in pools with crystal-clear water. The snail *Glyptophysa* survived only in those pools with large rocks on Mt Madden (and also Anderson Rocks and King Rocks: B V Timms unpubl. data) probably because the protected undersides of such rocks provide aestivation refuges. Chironomids and ceratopogonids were most common in pools with thicker organic sediments which may provide the most suitable habitat and food, but this was not investigated quantitatively.

As recorded in other studies (Bayly 1982, 1997; Pinder *et al.* 2000), regional endemism is high, mainly among the crustaceans which tend to have lower dispersability. The list includes many of the dominants such as *Branchinella longirostris, Limnadia badia, Pleurispina* spp. *Ceriodaphnia* n. sp., *Daphnia jollyi, Macrothrix hardingi, Bennelongia* sp 563, *Boeckella opaqua* and *Allotrissocladius* sp 1 (an insect). An addition to the list of endemic species is the new subspecies of *Triops* which lives in northern gnammas in this study but is found rarely in gnammas in the Hyden area (B Vanschoenwinkel pers.comm. 2011).

The high diversity and endemism of invertebrates in gnammas in the wheatbelt is typical of inland waters of southwestern Australia and applies to many invertebrate groups [e.g. *Branchinella* (Timms 2002, 2008); *Coxiella* (Pinder *et al.* 2002); chydorid cladocerans (R. Shiel pers.comm. 2008); *Daphnia (Daphniopsis)* (Hebert & Wilson 2000); mytilocyprinid and other ostracods (Halse & McRae 2004; Pinder *et al.* 2002); and *Parartemia* (Timms 2010)]. Diversity and endemism is believed to be promoted by past climate change and the role of isolated refugia, isolated granitic outcrops with their stressful but reliably filled seasonal pools being particularly ideal locations for speciation (Hopper *et al.* 1997).

Jocqué *et al.* (2007a) mentioned two basic classes of inhabitants in these gnammas, passive and active dispersers, while Williams (1985) based on Wiggins *et al.* 1980 recognised a more detailed classification of four types (I to IV). All the crustaceans (large and small branchiopods, copepods, cladocerans, ostracods), planarians and the snail *Glyptophysa* sp. belong to Wiggins *et al.*'s Group I [type (a) of Williams], the permanent residents capable of only passive dispersal. Almost all of these survive the desiccated period as resistant eggs, but the cyclopoid copepod *Mesocyclops laurentiisae* seems to pass the summer in some advanced copepodite stage (as do some overseas cyclopoids in winter: Smyly 1958), and the snail as quiescent adults. A few species belong to Wiggins *et al.*'s Group II [type (b) of Williams] which includes the residents capable of some active dispersal. Examples are some of the chironomids, including *Paraborniella tonnoiri*. These survive the dry summer as cryptobiotic 4th instars and the adults are capable of limited airborne dispersal during the wetted period (Jones 1971; Edwards 1968). The remainder belong to Group IV [type (c) of Williams]; they are all insects (hemipterans, coleopterans, various dipterans including some chironomids such as *Chironomus tepperi* living in the pools when wet, but surviving elsewhere during the dry period. Wiggins *et al.*'s type III does not need water for breeding; the only example in the present pools is the terrestrial trombidioid mites, which are really accidental members of the aquatic fauna of these pools. Williams (1985) dismissed this group and erected another type (d) that are found only in temporary waters moving from one to the next as they fill and dry over the year. There are no members of this group in these pools as generally all are wet in winter–spring and dry over summer–autumn.

The generalists [Group IV and type (c)] live in many types of habitats (Jocqué *et al.* 2007a). A prime example is the Coleoptera with many of the species recorded in gnammas widespread and found living in a variety of waters including swamps, marshes and freshwater and saline lakes (Pinder *et al.* 2000). Hendrich & Frey (2008) mentioned eight visiting species (to four granite outcrops), Pinder *et al.* (2000, 2002) 23 taxa (to nine granite outcrops), and the present study 16 species (to five granite outcrops), making 28 species altogether. This is the first study to find so many species breeding, with eight different type of larvae recorded. An exception to more generalists beetles appears to be *Paroster* which has some species focusing on pan gnammas, visiting them early in their existence to breed and during the wet phase utilising them to the exclusion of other pools in the area (B V Timms unpubl. data). Hendrich & Frey (2008) surmised that at least *P. baylyi* and *P. ursulae* may pass the summer as resistant eggs in pan sediments just like the crustaceans. This study suggests this is unlikely, as *Paroster* near *michaelseni* oversummers elsewhere, arrives to bred when the pans first fill, larvae grow in the pans during their wet phase (small in weeks 3–12, larger in weeks 12–18) and mature before the pans dry, giving a second peak of adults. They behave ecologically like the majority of insects and not like the crustaceans, and their life cycle is adapted to the hydrological regime of pan gnammas. The same does not apply to some of the other generalists found in gnammas, for instance odonates and many hemipterans did not complete their life cycle in 2010. Though this study did not focus on dispersal, the greater dispersal ability of the generalist insects *vis-á-vis* the passive crustaceans, is revealed by their appearing in more pools per rock than similarly classified uncommon crustaceans (cf. Tables 1 and 2).

Succession in these pools is explained largely by the tolerance model of Connell & Slatyer (1977) with perhaps some aspects of their inhibition model applying. In most pools the habitat changed little during the wetted period: plants quickly appeared in most pools but did not dominate the water column; salinity increased a little, but still well within tolerance limits; most pools had crystal-clear water throughout their existence. So successional stages associated with vast habitat changes as seen in the Pomborneit pool (in Victoria) studied by Lake *et al.* (1989) would not be expected. Neither were there major changes in predation pressure as seen in that study – the major predators, planarians and beetle larvae, were generally abundant throughout weeks 6–15 with certainly no obvious peak towards the end as in the Pomborneit study (Lake *et al.* 1989). It is possible that this pressure eliminated fairy shrimps in many pools and cladocerans then dominated, as predicted by Jocqué *et al.* (2007b). However, this study was too coarse to be sure of this and, besides, the averaging method of recording abundance and species richness in the pool sets blurred changes in individual pools. It would seem that most species in these pools developed largely independently of others, reaching their peak numbers and endurance according to their phenological characteristics, i.e. pool dynamics fall largely within the scope of the tolerance model of succession. The unusually short hydroperiod of 2010 was long enough for all the passive dispersers [Types I and II, (a) and (b)] to complete their life cycle, but not for some of the generalists [Types IV and (c)].

Presumably during a 'normal' year when hydroperiods extend to October and November all generalists complete their life cycle, but composition of invertebrate assemblages at such times is unknown. Based on 2010 data, it is predicted many pools would be dominated by *Limnadia badia, Boeckella opaqua* and various ostracods.

## ACKNOWLEDGEMENTS

I am grateful to Robert and Whispie Bayly, Sheangah and Dennis Collins, Mark Coleman and Bindy Datson for hospitality, to Whispie Bayly, Mary and John Squire, Wendy Timms, Melanie Timms, and John Vosper for field assistance on one or more sampling trips each, to the Department of Conservation for permission to work in the Mt Madden and Yanneymooning Nature Reserves, to Stuart Halse, Anna Leung, Koen Martens, Jane McRae, Russ Shiels, and Chris Watts, for help with identifications, to Jason Morton for assistance with multivariate analysis, to Stuart McVicar for assistance with Figures 4–9, Ian Bayly and Bran Vanschoenwinkel for comments on the manuscript and three anonymous reviewers for much advice.

## REFERENCES

Bayly I A E 1982. Invertebrates of temporary waters on granite outcrops in southern Western Australia. *Australian Journal of Marine and Freshwater Research* **33**, 599–606.

Bayly I A E 1997. Invertebrates of temporary waters in gnammas on granite outcrops in Western Australia. *Journal of the Royal Society of Western Australia* **80**, 167–172.

Bayly I A E, Halse, S A & Timms B V 2011. Aquatic invertebrates of rockholes in the south-east of Western Australia. *Journal of the Royal Society of Western Australia* **94**, 549–555.

Bishop J A 1974. The fauna of temporary rain pools in eastern New South Wales. *Hydrobiologia* **44**,319–323.

Clarke K R & Gorley R N 2001. PRIMER v5: user manual/tutorial. PRIMER-E, Plymouth.

Connell J H & Slatyer R O 1977. Mechansims of succession in natural communities and their role in community stability and organisation. *The American Naturalist* **111**, 1119–1144.

Edward D H D 1968. Chironomidae of temporary freshwaters. *Australian Society for Limnology Newsletter* **6**, 3–5.

Halse S A & McRae J 2004. New genera and species of 'giant' ostracods (Crustacea: Cyprididae) from Australia. *Hydrobiologia* **524**, 1–52.

Hart B T, Bailey P, Edwards R, Hortie K, McMahon A, Meredith, C & Swadling K 1991. A review of the salt sensitivity of the Australian freshwater biota. *Hydrobiologia* **210**, 105–144.

Hebert P D N & Wilson C C 2000. Diversity of the genus *Daphniopsis* in the saline waters of Australia. *Canadian Journal of Zoology* 78, 794–808.

Hendrich L & Frey H 2008. *Paroster baylyi* sp. n., *P. ursulae* sp. n. (Col. Dytiscidae, Hydroporinae) and the water beetle diversity of pan-gnammas on isolated granite outcrops in the mallee of south-western Australia. *Zootaxa* 1704, 27–41.

Hopper S D, Brown A P & Marchant N G 1997. Plants of Western Australian granite outcrops. *Journal of the Royal Society of Western Australia* 80, 141–158.

Jocqué M 2007. Community structuring processes in temporary freshwater rock pools. PhD thesis, Katholieke Universiteit, Leuven (unpubl.).

Jocqué M, Timms B V & Brendonck L 2007a. A contribution on the biodiversity and conservation of the freshwater fauna of rocky outcrops in the central Wheatbelt of Western Australia. *Journal of the Royal Society of Western Australia* **90**, 137–142.

Jocqué M, Vanschoenwinkel B & Brendonck L 2007b. Anostracan monopolisation of early successional phases in temporary waters. *Archiv für Hydrobiologie* 176, 127–132.

Jocqué M, Vanschoenwinkel B & Brendonck L 2010. Freshwater rock pools: a review of habitat characteristics, faunal diversity and conservation value. *Freshwater Biology* **55**, 1587–1602.

Jones R E 1971. The ecology of some species of Diptera on granite outcrops. PhD thesis, University of Western Australia, Perth (unpubl.).

Lake P S, Bayly I A E & Morton D W 1989. The phenology of a temporary pond in western Victoria, Australia, with special reference to invertebrate succession. *Archiv für Hydrobiologie* **115**, 171–202.

Pinder A M, Halse S A, Shiel R J, Cale D C & McRae J M 2002. Halophilic aquatic invertebrates in the wheatbelt region of south-western Western Australia. *Verhandlungen Internationale Vereiningung Limnologie* **28**, 1687–1694.

Pinder A M, Halse S A, Shiel R J & McRae J M 2000. Granite outcrop pools in south-western Australia: foci of diversification and refugia for aquatic invertebrates. *Journal of the Royal Society of Western Australia* **83**, 149–161.

Smyly W J P 1958. The Cladocera and Copepoda (Crustacea) of the tarns of the English Lake District. *Journal of Animal Ecology* **27**, 87–103.

Timms B V 2002. The fairy shrimp genus *Branchinella* Sayce (Crustacea: Anostraca: Thamnocephalidae) in Western Australia, including a description of four new species. *Hydrobiologia* **186**, 71–89.

Timms B V 2006. The large branchiopods (Crustacea: Branchiopoda) of gnammas (rock holes) in Australia. *Journal of the Royal Society of Western Australia* **89**, 163–173.

Timms B V 2008. Further studies on the fairy shrimp genus *Branchinella* (Crustacea, Anostraca, Thamnocephalidae) in Western Australia, with descriptions of new species. *Records of the Western Australian Museum* **24**, 289–306.

Timms B V 2010. Six new species of the brine shrimp *Parartemia* Sayce 1903 (Crustacea: Anostraca: Artemiina) in Western Australia. *Zootaxa* **2715**, 1–35.

Twidale C R & Corbin E M 1963. Gnammas. *Revue de Géomorphologie Dynamique* **14**:1–20.

Vanschoenwinkel B, Hulsman A, de Roeck, E, de Vries C, Seaman M & Brendonck L 2009. Community structure in temporary rock pools: disentangling the effects of habitat size and hydroregime. *Freshwater Biology* **54**, 1487–1500.

Vanschoenwinkel B, Waterkeyn A, Jocqué M, Boven L, Seaman M & Brendonck L 2010. Species sorting in space and time—the impact of disturbance regime on community assembly in a temporary pool metacommunity. *Journal of the North American Benthological Society* **29**, 1267–1278.

Waterkeyn A, Grillas P, Vanschoenwinkel B & Brendonck L 2008. Invertebrate community patterns in Mediterranean wetlands along hydroperiod and salinity gradients. *Freshwater Biology* **53**, 1808–1822.

Wiggens G B, Mackay R J & Smith I M 1980. Evolutionary and ecological strategies of animals in annual temporary pools. *Archiv für Hydrobiologie Supplement* **58**, 97–206.

Williams W D 1985. Biotic adaptations in temporary lentic waters, with special reference to those in semi-arid and arid regions. *Hydrobiologia* **125**, 85–110.

*Manuscript received 1 July 2011; accepted 26 March 2012*

**Appendix 1** Seasonal changes in abundance indices for selected species at the five sites.

| **Mt Madden** | **24 May** | **17 Jun** | **10 Jul** | **1 Aug** | **24 Aug** | **12 Sep** | **3 Oct** |
|---|---|---|---|---|---|---|---|
| Planarians (3 spp.) | - | 1.0 | 2.3 | 1.9 | 6.0 | 5.6 | 4.8 |
| Nematode | - | 2.2 | 3.5 | 2.4 | 2.1 | 4.0 | 1.4 |
| Branchiopod larvae | 5.9 | - | - | - | - | - | - |
| *Branchinella longirostris* | - | 5.0 | 3.1 | 1.9 | 0.7 | 1.0 | 0.7 |
| *Limnadia badia* | - | 7.0 | 7.3 | 5.5 | 5.2 | 5.3 | 2.7 |
| *Boeckella opaqua* | 3.6j | 19.0 | 20.5 | 20.3 | 21.7 | 17 | 7.3 |
| *Metacyclops laurentiisae* | 1.5a | 10.5 | 0.3 | 0.6 | 0.2 | 0.1 | 0.4 |
| Harpacticoid sp 674 | - | 1.0 | 0.4 | - | - | - | - |
| *Ceriodaphnia n.*sp. | - | 8.1 | 14.6 | 19.9 | 13.7 | 14.0 | - |
| *Moina australiensis* | - | 1.6 | 1.3 | - | 1.3 | 1.7 | - |
| *Macrothrix hardingi* | 3.6 | - | - | - | - | - | - |
| Macrothricidae (6 spp.) | - | 1.3 | 0.6 | 2.0 | 0.7 | 0.1 | 0.1 |
| Chydoridae (6 spp.) | 0.1 | 0.4 | 1.5 | 3.2 | 5.5 | 2.3 | 3.3 |
| Ostracoda (8 spp.) | 0.1 | 1.1 | 3.4 | 5.5 | 8.3 | 6.3 | 3.2 |
| Odonata larvae | - | - | - | - | - | 0.4 | 0.1 |
| Hemiptera (4 spp.) | 0.2 | 0.3 | 0.1 | 0.2 | 0.2 | 0.3 | 0.1 |
| *Paroster* adults | 0.4 | 0.4 | 1.0 | 0.2 | - | - | - |
| Other Colepotera (6 spp.) | 0.1 | 0.1 | 0.1 | 0.4 | 0.3 | 0.2 | - |
| Dytiscidae larvae (3 spp.) | - | 0.1 | 0.2 | 0.2 | 0.2 | 0.8 | - |
| chironomids (3 spp.) | - | 0.1 | 1.2 | 1.2 | 0.4 | 0.9 | - |
| *Dasyhelia* sp. | - | - | - | - | 0.1 | - | 1.8 |
| *Aedes alboannulatus* | - | - | - | 0.1 | - | - | - |
| *Glyptophysa* | - | 5.6 | 4.6 | 11.0 | 14.0 | 14.0 | 10.0 |

J, juveniles; a, adults

| **Hyden Rock** | **24 May** | **17 Jun** | **12 Jul** | **1 Aug** | **24 Aug** | **12 Sep** | **4 Oct** |
|---|---|---|---|---|---|---|---|
| Planarians (3 spp.) | 0.2 | 1.5 | 3.2 | 5.0 | 4.4 | 2.3 | 1.0 |
| Nematode | 5.3 | 3.9 | 10.1 | 9.7 | 9.3 | 0.9 | 1.3 |
| Branchiopod larvae | 0.1 | - | - | - | - | - | - |
| *Branchinella longirostris* | - | 0.5 | 0.1 | 0.1 | - | - | - |
| *Limnadia badia* | - | 2.5 | 2.5 | 5.4 | 2.7 | 1.8 | 0.3 |
| *Boeckella opaqua* | 0.3 | 5.3 | 13.0 | 20.0 | 16.7 | 10.0 | 1.3 |
| *Ceriodaphnia* n.sp. | - | 3.3 | 10.0 | 15.6 | 14.7 | 7.7 | - |
| *Moina australiensis* | - | - | 0.1 | - | 0.1 | 1.7 | 1.3 |
| Other Macrothricidae (3 spp.) | - | 0.7 | 0.2 | 0.8 | 1.6 | 0.7 | - |
| Chydroidae (8 spp.) | - | 0.4 | 1.5 | 2.6 | 2.2 | 1.1 | 0.2 |
| Ostracods (7 spp.) | - | 1.0 | 2.1 | 5.3 | 5.8 | 2.6 | 1.5 |
| Hemiptera (4 spp.) | - | 0.3 | - | 0.1 | 0.3 | 0.5 | 0.4 |
| *Paroster* adults | 0.3 | - | - | - | - | 0.1 | - |
| Other beetle adults (8 spp.) | 0.1 | 0.1 | 0.1 | 0.2 | 0.1 | 0.1 | - |
| Beetle larvae(3 spp.) | - | - | 0.1 | 0.4 | 0.4 | 0.4 | 0.4 |
| Chironomids (4 spp.) | 1.9 | 0.8 | 1.1 | 1.5 | 0.6 | 0.7 | 0.3 |
| *Dasyhelia* sp. | 0.5 | 2.6 | 2.5 | 2.7 | 0.1 | - | - |
| *Aedes alboannulatus* | - | - | 2.5 | - | 0.3 | - | - |

| **Yanneymooning Rock** | **25 May** | **18 Jun** | **11 Jul** | **2 Aug** | **25 Aug** | **13 Sep** | **5 Oct**[1] |
|---|---|---|---|---|---|---|---|
| Planarians (2 spp.) | 0.1 | 1.5 | 1.6 | 3.9 | 1.5 | 1.4 | - |
| Nematode | - | 2.4 | 0.2 | 0.7 | - | 0.1 | - |
| Branchipod larvae | 4.3 | - | - | - | 2.7 | 3.7 | - |
| *Branchinella longirostris* | 2.0j | 4.0j | 9.7 | 10.3 | 7.7 | 6.7 | - |
| *Limnadia badia* | 2.3j | 5.1 | 5.5 | 8.1 | 4.0 | 5.8 | - |
| *Caenestheriella mariae* | - | - | - | 0.1 | 0.1 | 0.3 | - |
| *Boeckella opaqua* | - | 3.9 | 12.3 | 15.3 | 9.7 | 10.0 | - |
| *Ceriodaphnia* n.sp. | - | 0.2 | - | - | - | - | - |
| *Daphnia jollyi* | - | 0.1 | 1.5 | 1.7 | - | - | - |
| *Macrothrix hardingi* | - | 0.1 | 4.0 | 10.0 | 3.7 | 5.4 | - |

| **Yanneymooning Rock *(cont.)*** | **25 May** | **18 Jun** | **11 Jul** | **2 Aug** | **25 Aug** | **13 Sep** | **5 Oct[1]** |
|---|---|---|---|---|---|---|---|
| Other Macrothricidae (3 spp.) | - | 0.5 | 1.4 | 2.3 | 1.0 | 0.2 | - |
| Chydoridae (5 spp.) | - | 0.2 | 1.4 | 3.5 | 1.5 | 1.2 | - |
| Ostracoda (6 spp.) | - | 1.3 | 2.6 | 3.5 | 2.1 | 1.8 | - |
| Hemiptera (4 spp.) | - | 0.1 | 0.6 | 0.1 | 0.6 | 0.8 | - |
| Odonata | - | - | 0.3 | - | - | 0.2 | - |
| *Paroster* sp. | 7.5 | 2.2 | 1.2 | 0.6 | 0.8 | 3.1 | - |
| other beetles (2 spp.) | 0.1 | 0.3 | 0.7 | 0.3 | 0.4 | 0.2 | - |
| beetle larvae (2 spp.) | - | 0.5 | 0.3 | 0.9 | 0.7 | 0.7 | - |
| chironomids (4 spp.) | 2.7 | 2.8 | 0.8 | 0.3 | 0.1 | 0.8 | - |
| *Dasyhelia* sp. | - | - | 0.1 | - | 0.4 | 2.0 | - |
| *Aedes alboannulatus* | - | 0.5 | 1.0 | 0.4 | - | - | - |
| Trombidioid mite | 0.1 | 0.1 | 0.1 | - | - | 0.2 | - |

[1] Dry
j, juveniles

| **Bullamanya Rock** | **26 May** | **19 Jun** | **12 Jul** | **3 Aug** | **26 Aug** | **14 Sep** | **5 Oct** |
|---|---|---|---|---|---|---|---|
| Planarians (2 sp.) | 0.1 | 2.0 | 3.5 | 2.2 | 1.1 | 0.1 | 0.1 |
| Nematodes | 1 | 0.8 | 0.3 | 0.3 | 0.3 | 1.3 | 1.3 |
| Branchiopod larvae | 17.2 | - | - | - | 3.7 | - | - |
| *Branchinella longirostris* | - | 12 | 11.5 | 12.0 | 3.0 | 5.9 | - |
| *Limnadia badia* | 0.1 | 12 | 12.5 | 12.3 | 4.3 | 8.7 | - |
| *Caenestheriella mariae* | - | 1.6 | 6.1 | 7.7 | 4.3 | 2.8 | 0.3 |
| *Triops* n. sp. | - | 2.2 | 0.1 | - | - | 0.4 | 4.0 |
| *Boeckella opaqua* | - | 17.9 | 17.6 | 15.3 | 12.0 | 14.3 | 2.3 |
| *Daphnia jollyi* | - | - | 0.1 | 1.7 | - | - | - |
| *Moina australiensis* | - | - | - | - | - | 0.3 | 1.3 |
| *Macrothrix hardingi* | - | 3.3 | 10.3 | 10 | 6.3 | 8.4 | - |
| Other Macrothricidae (4 spp.) | - | 0.5 | 1.2 | 2.0 | 2.4 | 1.3 | 0.2 |
| Chydoridae (5 spp.) | - | - | 0.4 | 3.6 | 1.1 | 0.8 | 0.1 |
| Ostracods (7 spp.) | - | 1.8 | 2.8 | 2.9 | 3.8 | 1.6 | 0.5 |
| *Anisops gratus* | - | 0.5 | - | - | - | 0.2 | 0.1 |
| Dragonfly larvae | - | - | - | - | 0.4 | 1.7 | 2.7 |
| *Paroster* beetle | 1.7 | 0.3 | - | - | 0.3 | 0.5 | 1.0 |
| Other beetle adults (5 spp) | - | 0.1 | 0.1 | 0.1 | 0.3 | 0.2 | 0.1 |
| Beetle larvae (3 spp.) | - | 0.2 | 0.9 | 1.0 | 0.9 | 0.1 | - |
| *Chironomus tepperi* | 0.7 | 2.5 | 5.3 | 1.4 | 0.8 | 0.3 | - |
| Other chironomids (5 spp.) | 0.3 | 1.4 | 3.2 | 1.3 | 1.4 | 0.8 | - |
| *Aedes alboannulatus* | 2.0 | 1.0 | 0.5 | - | - | - | - |
| *Dasyhelia* sp. | - | - | 0.5 | 3.3 | 5.0 | - | - |
| Trombidioid mites | 0.1 | 0.1 | 0.1 | - | - | - | - |

| **Walga Rock** | **27 May** | **20 Jun** | **15 Jul** | **4 Aug[1]** | **14 Sep** | **6 Oct[1]** |
|---|---|---|---|---|---|---|
| Nematodes | 1.8 | 2.7 | - | - | 3.0 | - |
| Branchiopod larvae | 4.0 | - | 17.2 | - | 16.8 | - |
| *Branchinella longirostris* | 5.3 | 3.0 | - | - | - | - |
| *Caenestheriella mariae* | 4.3 | 5.0 | - | - | - | - |
| *Triops* n. sp. | 1.0 | 1.1 | - | - | 6.3 | - |
| *Boeckella opaqua* | - | 5.3 | - | - | - | - |
| Ostracods (2 spp.) | 0.6 | 0.4 | - | - | - | - |
| Hemiptera (2 spp.) | 0.4 | 4.8 | - | - | 0.1 | - |
| *Paroster* sp. | - | - | 1.6 | - |  | - |
| Other beetles (4 spp.) | - | 0.1 | 0.6 | - | 0.5 | - |
| Beetle larvae | - | 0.7 | 0.4 | - | - | - |
| Chironomids (2 spp.) | 3.7 | 3.9 | 4.5 | - | 5.1 | - |
| *Dasyhelia* sp. | - | 3.5 | 3.5 | - | 5.7 | - |

[1] Dry

Journal of the Royal Society of Western Australia, 95: 29–51, 2012

# Aquatic invertebrates of the Hutt River and Hutt Lagoon catchments, Western Australia

A M PINDER*, K QUINLAN, D J CALE & A E LEUNG†

*Department of Environment & Conservation, PO Box 51, Wanneroo, WA 6946, Australia*

* *Corresponding author: ✉ adrian.pinder@dec.wa.gov.au*

† *Present address: Pheonix Environmental Sciences, 1/511 Wanneroo Road, Balcatta, WA 6021, Australia*

The Hutt River and Hutt Lagoon catchments lie along the coast of the mid-west region of Western Australia. An earlier study suggested they were amongst a set of catchments that efficiently represent salinity-threatened biota in the agricultural southwest of the State. Several of the other catchments in that set have been included in a program to protect their biodiversity assets. This paper reports on the diversity and biogeographic affinities of the aquatic invertebrate fauna of the combined Hutt catchments. We also assess the extent to which this fauna is complementary to those of other catchments and wetland suites managed for conservation in southern Western Australia. A total of 249 invertebrate species were collected from these catchments. This fauna includes species that have primarily northern Australian distributions and species that are more common in the higher rainfall southwest, demonstrating that the catchments lie within a zone of north–south faunal transition. It is unlikely that any individual species are unique to these catchments. However, the catchments do support a fauna that is dissimilar in composition to faunas of other wetland suites and catchments of the agricultural southwest for which there is similar information. Faunal composition varied greatly between the wetland habitats surveyed, with the freshwater springs and creeks representing particularly important habitats within the region. Six groups of wetlands are recognised based on the composition of their invertebrate communities and these are used as a framework for discussing conservation issues.

**KEYWORDS: aquatic invertebrates, conservation, Hutt Lagoon, Hutt River, rivers, springs, Western Australia, wetlands.**

## INTRODUCTION

Aquatic biodiversity in the Western Australian Wheatbelt was surveyed by Pinder *et al.* (2004) and Lyons *et al.* (2004) as part of a comprehensive survey of the region (Keighery *et al.* 2004). This is one of a number of large-scale surveys that have greatly increased knowledge of the State's aquatic biodiversity over the last two decades (Davis *et al.* 1993; Halse *et al.* 2000a; Horwitz 1997; Pinder *et al.* 2004, 2010a). Such surveys have a relatively sparse distribution of study sites, reflecting resource constraints in relation to the large areas surveyed. Smaller catchments and wetland areas identified as potentially high conservation value, sometimes as a result of the larger surveys (McKenzie *et al.* 2000; Commonwealth of Australia and the State of Western Australia 1999; Walshe *et al.* 2004), frequently require more intensive studies for local conservation planning. In the Wheatbelt, data from the regional survey were used by Walshe *et al.* (2004) to identify a set of catchments that 'efficiently represented [salinity threatened] diversity'. Several of those catchments have now been included in a 'Natural Diversity Recovery Catchment Program' (http://www.dec.wa.gov.au/content/view/449/949/) that aims to manage catchments for protection of their natural values. As recommended by Walshe *et al.* (2004), surveys and/or monitoring have been undertaken at some of the Wheatbelt wetlands to provide biodiversity data for local conservation planning (Aquatic Research Laboratory 2009; Cale 2008; Department of Environment and Conservation 2006). This paper reports on a survey of aquatic invertebrates in another of the Walshe *et al.* (2004) catchments—the Greenough (Hutt) in the mid-west of Western Australia. This survey joins a growing list of studies of catchments or wetland complexes that are providing an understanding of fine-scale aquatic biodiversity patterning and filling gaps in the larger surveys (Edward *et al.* 1994; Halse *et al.* 1996, 1998, 2000b; Pusey & Edward 1990; Stewart 2009; Storey *et al.* 1993, 2011; Timms 2009).

The objectives of this paper are to (i) describe the aquatic invertebrate communities of the Hutt River and Hutt Lagoon catchments; (ii) investigate the biogeographic affinities of the fauna; (iii) assess the extent to which the catchments support a fauna already represented in other wetlands and catchments managed for conservation in the southwest agricultural zone; and (iv) identify priorities for aquatic invertebrate conservation in these catchments.

## STUDY AREA

The Walshe *et al.* (2004) Greenough (Hutt) catchment incorporates four of the Greenough Basin sub-catchments. These are the two sub-catchments of the Hutt River (shown merged on Figure 1), the northernmost sub-catchment of the Greenough Coastal catchment (labelled as the Hutt Lagoon catchment on Figure 1) and a small northern sub-catchment of the Bowes River Catchment. Only the first three of these sub-catchments are included in our study (Figure 1) and they are jointly called the Hutt catchments in this paper. These are located on the mid-west coast about 75 km north of

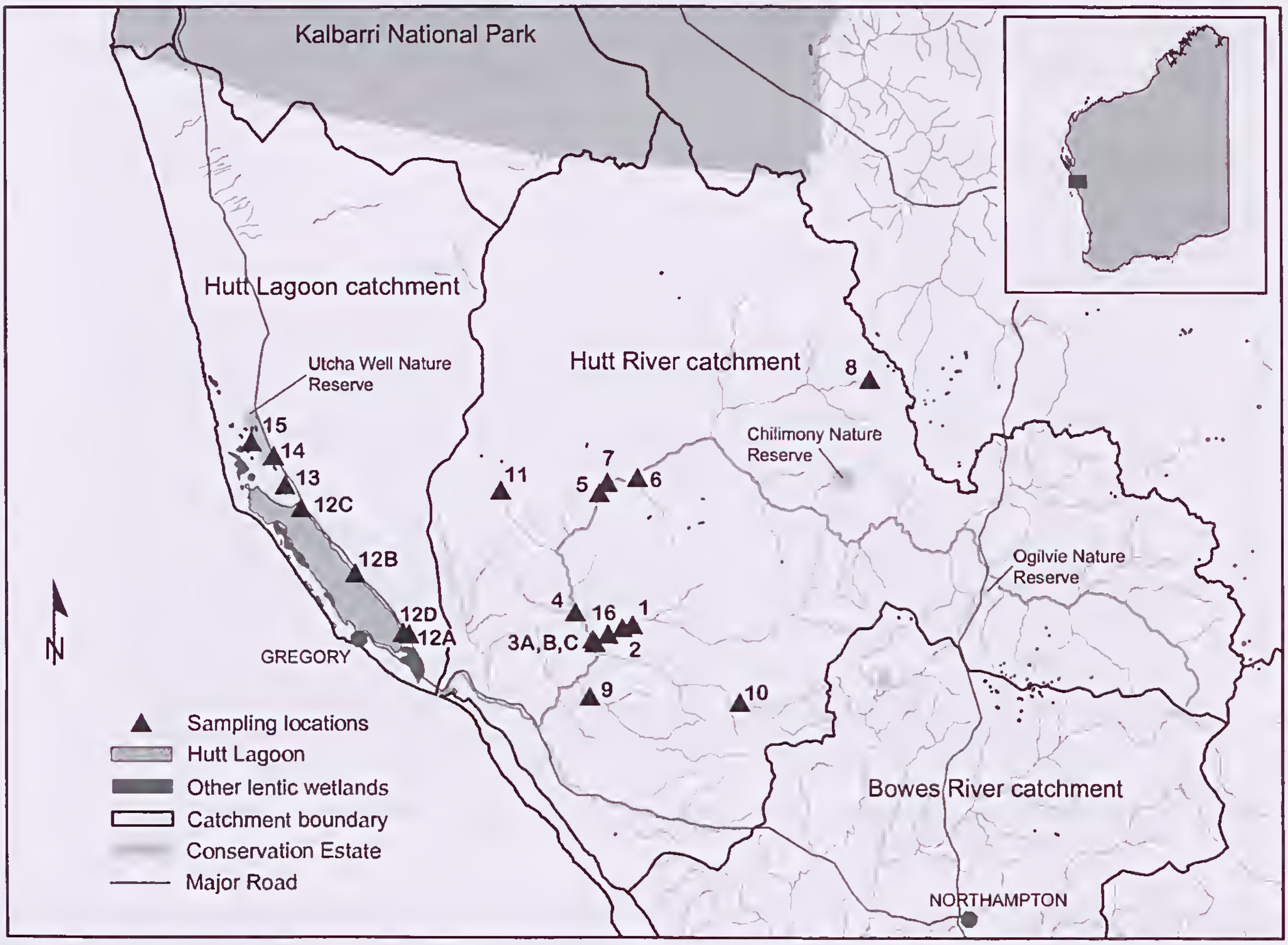


**Figure 1.** Map of the Hutt catchments showing locations of sampled sites and boundaries of the Hutt River and Hutt Lagoon catchments.

Geraldton and occupy about 200 000 ha (8.9%) of the Geraldton Hills IBRA subregion (Australian Government 2004). The 'mid-west' referred to in this paper is that semiarid to arid region of the State between the more temperate southwest and the Pilbara region in the north extending inland from the coast towards the desert regions. The southwest of this area overlaps with the northern extent of region of dryland agricultural zone known as the Wheatbelt.

The Hutt River catchment is dominated by the 60 km-long main channel of the Hutt River. In its upper catchment, low gradient creeks lie on a 220–260 mASL plateau and these are mostly salinised. On this plateau there are also numerous seasonal secondarily saline wetlands. The middle and lower parts of the catchment are more dissected and include perennial spring-fed tributaries, many of which are fresh. Rainfall-dominated flows (primarily in winter and spring) carry high salt loads from the upper catchment. In summer, low-salinity groundwater discharge usually becomes the dominant source of water and the river then has lower salinity. Hutt Lagoon is a 12 km long x 2 km wide, shallow (<1 m) hypersaline evaporative birrida. This is the old estuary of the Hutt River, now naturally isolated from the ocean (Arakel & Moulton 1986) but receiving marine water via subsurface flows due to the lagoon lying below sea-level. On the low-lying flats north of the lagoon are numerous swamps and marshes, including Utcha Swamp. Hutt Lagoon and Utcha Swamp are listed in the Directory of Important Wetlands in Australia (Environment Australia 2001).

The region has mild wet winters and hot dry summers. Mean annual rainfall increases from about 350 mm at Binnu, just east of the Hutt River catchment, to 405 mm at Lynton (near Gregory) on the coast. Rainfall was well below average in 2007 (222 mm at Binnu and 212 mm at Lynton) but summer 2007/08 rainfall (86.8 mm) was much higher than average (25.1 mm), falling mostly on 11 December 2007 and 21 February 2008. The higher than average summer rainfall meant that the Hutt River did not freshen up in summer, as it normally does when flow from the freshwater springs becomes dominant.

Land use in the Geraldton Hills subregion is primarily dryland agriculture (65.8%), with lesser areas of conservation (13.8%), grazed native pastures (13.2%) and other crown lands (6.5%) (Desmond & Chant 2002). Over 98% of the area in this subregion's conservation estate is contained in two reserves: Kalbarri National Park (183 004 ha) and Wandana Nature Reserve (54 821 ha), both of which are entirely outside the Hutt catchments. Only 0.25% of land within the Hutt catchments is in conservation estate: Chilimony Nature Reserve, Nature Reserve 12657 and Utcha Well Nature Reserve, the latter fragmented into several parcels (Figure 1). Clearing of native vegetation for agriculture has been extensive within the catchments and has resulted in altered groundwater and surface water hydrology and associated secondary salinisation, especially in upper parts of the Hutt River catchment. Stock access and feral pig activity in the Hutt River channel and riparian zone have contributed to weed invasion, bank erosion, siltation of streams and poor water quality in the Hutt River (Department of Environment 2005).

In a previous invertebrate survey, Pinder *et al.* (2004) sampled aquatic invertebrates at four sites in the Hutt catchments in July 1999: Yarder Gully, Yerina Spring, Hutt Lagoon and Utcha Swamp. All of these wetlands were re-sampled during the present project, but not necessarily at the same location (Table 1). Hutt Lagoon was also sampled in October 2008 by Nowicki *et al.* (2009). These data are included in our analyses.

## METHODS

### Study sites

Twenty-one sites have been sampled in total (Table 1). Eighteen sites were sampled for this survey, some of which were also sampled by Pinder *et al.* (2004), and three additional sites were sampled during previous or subsequent studies (Nowicki *et al.* 2009; Pinder *et al.* 2004). In the Hutt River catchment, sites were located along the main channel of the middle to lower Hutt River (sites 3A and C and sites 4–6), some of the main tributaries (sites 2, 9, 10 and 16) and some of the springs and seepages feeding into the river or tributaries (sites 1, 3B, 7, 8 and 11). In the Hutt Lagoon catchment, the main body of the lagoon was sampled at sites 12A to 12C, an area of low salinity seepage on the eastern shore of the lagoon was sampled at site 12D and some of the wetlands north of the lagoon were sampled (sites 13–15). Gaps in sampling include small playas and saline streams in the upper Hutt River catchment, wetlands in dunes to the west of Hutt Lagoon and ephemeral creeks draining the hills east of Hutt Lagoon.

Most sampling was carried out in spring (4 samples in 1999, 17 samples in 2007 and 1 sample in 2008). Three sites (3A, 3C and 4) plus one extra site (3B) were sampled in February 2008. This gives a total of 26 samples (Table 1). The February 2008 sampling was undertaken to examine whether the lower flow and salinity expected in the Hutt River at that time of year (due to flows becoming dominated by the fresher spring-fed tributaries), resulted in altered community composition compared to spring.

### Water quality

Electrical conductivity, pH and water temperature were measured in the field using a WTW WP-81 meter. Flow was measured using a Hydrological Services OSS-PC1 current meter, except where water was too shallow and then flow was estimated by timing the movement of a neutral buoyancy object (generally a eucalypt nut). At least 1000 mL of water was passed through a glass microfibre filter paper and the paper retained and frozen for analysis of chlorophyll and the filtrate was passed through a 0.45 μm pore filter paper and frozen for analysis of total filterable nitrogen and phosphorus. Unfiltered water was collected for analysis of colour, hardness, alkalinity, ionic composition and turbidity.

### Invertebrates

On each sampling occasion, two invertebrate samples were collected: a plankton sample using a net with 50 μm mesh to sweep through the water column and gently through sparse vegetation and one benthic sample using a net with 250 μm mesh to sample the dominant habitats (*e.g.* open water, detritus, vegetation and substrates). Each sample involved sweeping for a total of about 50 m (usually not contiguous). The benthic samples were elutriated in the field to remove heavier inorganic material, leaves and woody debris were washed and discarded and then the sample was preserved in ethanol. The plankton sample was preserved in buffered formalin. The entire contents of each sample were sieved and sorted in the laboratory and representatives of each taxon seen during sorting were removed. Invertebrates were identified to species level where possible.

### Data analysis

To assess robustness of cluster groupings several methods were used (Legendre & Legendre 1998). Non-hierarchical k-means clustering (into six groups) was performed using the 'pam' function in the R package 'Vegan' (Oksanen *et al.* 2008; R Development Core Team 2011) and agglomerative clustering was performed using the 'agnes' function in the R package 'Cluster' (Maechler *et al.* 2007), with average, complete and flexible linkage methods, the latter with beta = -0.1. Co-phenetic variation (using the 'cophenetic' and 'correlation' functions in R) was used to investigate how well the clustering represented original inter-sample distances. The function 'simprof' in the R package 'Clustsig' (Whitaker & Christman 2010) was used to identify significant clusters in dendrograms.The Chao2 species richness estimator (Chao 1987) in Estimate S (Colwell 2006) was used to estimate total species richness in the Hutt catchments.

To compare community composition between Hutt catchment wetlands and wetlands in other Walshe *et al.* (2004) catchments, all available data from these catchments were combined in a non-metric multidimensional scaling (nMDS) ordination using Primer-E Ltd (2008). For this analysis, some manipulation of the matrix was required where the level of taxonomic resolution and nomenclature used for undescribed species was irreconcilable between the Buntine–Marchagee dataset (Aquatic Research Laboratory 2009 and reports therein) and the datasets for other recovery catchments: Toolibin (Halse *et al.* 2000b), Drummond (Cale 2005 and unpublished data), Bryde (Cale *et al.* 2004, 2008) and Warden (Pinder *et al.* 2010b and unpublished data).

## RESULTS

### Water physico-chemistry

Table 2 contains the water chemistry data for all samples. Of the 22 samples collected in spring 1999, 2007 or 2008,

**Table 1** List and descriptions of sites sampled in the Hutt catchments.

| Site no. | Site name | Date(s) sampled | Grid reference (50J) | Description |
|---|---|---|---|---|
| 1 | Yarder Gully headwater spring | 11 Sep 2007 | 6879876 247324 | Spring running south of main creek line of Yarder Gully with seepage areas, shallow trickling water and muddy pools amongst sedges and ferns |
| 2 | Yarder Gully | 11 Sep 2007 | 6879663 246685 | Reach of Yarder Gully flowing through dense sedges |
| 3A | Hutt River at Yarder Gully confluence | 12 Sep 2007<br>25 Feb 2008 | 6878960 244831 | Hutt River immediately upstream and including Yarder Gully confluence |
| 3B | Hutt River rock pool seepage | 12 Sep 2007 | 6878960 244831 | Shallow rock pools capturing seepage which flows into the Hutt River just down stream of the Yarder-Hutt confluence. |
| 3C | Hutt River downstream of Yarder Gully | 25 Feb 2008 | 6878740 244987 | Hutt River immediately downstream of Yarder Gully confluence |
| 4 | Hutt River on Glenorie Station | 11 Sep 2007<br>25 Feb 2008 | 6880697 243788 | Braided reach downstream of two seepages from eastern bank |
| 5 | Hutt River south of Gregory Spring | 13 Sep 2007<br>26 Feb 2008 | 6888124 245272 | Reach with intact vegetation on both sides and passes over bedrock and silty areas. Downstream of seepage from Gregory Spring |
| 6 | Hutt River north of Gregory Spring | 13 Sep 2007 | 6889103 247628 | Silty reach upstream of Gregory Spring |
| 7 | Gregory Spring | 13 Sep 2007 | 6888774 245773 | A groundwater seepage area with sedges and small pools up to 3 cm deep and (when wet) with water trickling south to the adjacent Hutt River |
| 8 | Feast Soak | 14 Sep 2007 | 6895238 262202 | A sedge-filled soak with small areas of shallow open water. The resulting creek line is highly degraded but the spring itself is in somewhat better condition |
| 9 | Harry Spring Creek | 14 Sep 2007 | 6875374 244637 | A heavily wooded reach of a freshwater creek flowing north from Harry Spring. Channel heavily silted but includes areas of bedrock and overhanging vegetation |
| 10 | Creek next to Swamp Road | 12 Sep 2007 | 6875065 254012 | Narrow deeply incised creek adjacent to Swamp Road |
| 11 | Yerina Spring | 14 Sep 2007<br>22 July 1999 | 6888276 239110 | Sedgeland groundwater seepage with wettest areas amongst *Typha* or where a roadway impedes seepage (site SPS190 of Pinder *et al.* 2004) |
| 12A | Hutt Lagoon site A | 15 Sep 2007 | 6879372 233000 | An area of low salinity groundwater seepage in sedges on SE shore of lagoon |
| 12B | Hutt Lagoon site B | 15 Sep 2007 | 6883079 230016 | Eastern edge of main water-body of lagoon |
| 12C | Hutt Lagoon site C | 09 Oct 2008 | 6887130 226585 | North-eastern corner of lagoon (site RCM028 of Nowicki *et al.* 2009) |
| 12D | Hutt Lagoon site D | 21 Jul 1999 | 6879372 232800 | South-eastern end of lagoon (site SPS189 of Pinder *et al.* 2004) |
| 13 | *Baumea/Cyperus* fringed swamp | 15 Sep 2007 | 6888618 225663 | Hyposaline wetland with areas of open water surrounded by very dense stands of *Baumea articulata* and *Cyperus laevigatus* |
| 14 | Utcha Swamp | 10 Sep 2007<br>21 July 1999 | 6890446 224944 | Swamp with dense stands of submerged macrophytes and severe *Typha* encroachment (SPS188 of Pinder *et al.* 2004) |
| 15 | Sedge fringed flats north of Hutt Lagoon | 15 Sep 2007 | 6891302 223555 | Shallow sedge-fringed subsaline flats north of Hutt Lagoon |
| 16 | Yarder Gully | 23 Jul 1999 | 6879280 245787 | Braided open reach of Yarder Gully (site SPS192 of Pinder *et al.* 2004) |

**Table 2** Environmental data for wetland sites sampled in the Hutt catchments

| Site no. | Date | Cluster group | Depth of invertebrate sample (cm) | pH | Total filterable nitrogen (µg/L) | Total filterable phosphorus (µg/L) | Nitrite/Nitrate (µg/L) | Chlorophyll (µg/L) | Water temperature (°C) | Maximum flow (m/s) | Turbidity (NTU) | Colour (TCU) | Conductivity (µs/cm) | TDS (g/L) | Alkalinity (mg/L) | Hardness (mg/L) | Silica (mg/L) | $Na^+$ (mg/L) | $Ca^{2+}$ (mg/L) | $Mg^{2+}$ (mg/L) | $K^+$ (mg/L) | $Cl^-$ (mg/L) | $HCO_3^-$ (mg/L) | $CO_3^{2-}$ (mg/L) | $SO_4^{2-}$ (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 11 Sep 2007 | 1 | 10 | 7.38 | 330 | 30 | 5 | 4.5 | 16.8 | 0 | 61 | 73 | 1298 | 0.68 | 28 | 120 | 49 | 173 | 7.8 | 23.4 | 8.1 | 335 | 34 | 0.5 | 47.1 |
| 3B | 12 Sep 2007 | 1 | 40 | 6.2 | 3600 | 130 | 5 | 11 | 15.5 | 0 | 11 | 590 | 13420 | 8.80 | 120 | 1100 | 31 | 2160 | 64.1 | 240 | 55 | 4220 | 146 | 0.5 | 403 |
| 9 | 14 Sep 2007 | 1 | 45 | 7.09 | 870 | 10 | 120 | 10 | 17.5 | 45 | 53 | 52 | 4600 | 2.60 | 33 | 460 | 25 | 675 | 35.3 | 91.3 | 15.6 | 1270 | 40 | 0.5 | 155 |
| 10 | 12 Sep 2007 | 1 | 20 | 7.31 | 390 | 10 | 5 | 6 | 19.6 | 1 | 0.9 | 37 | 4540 | 2.50 | 33 | 460 | 43 | 664 | 33.8 | 89.9 | 10.8 | 1340 | 40 | 0.5 | 112 |
| 11 | 14 Sep 2007 | 1 | 10 | 6.78 | 6400 | 30 | 4400 | 8.5 | 18.5 | 0 | 1.3 | 0.5 | 1444 | 0.88 | 35 | 90 | 82 | 242 | 6.2 | 18.1 | 3.4 | 379 | 43 | 0.5 | 89.4 |
| 11 | 22 Jul 1999 | 1 | 20 | 6.16 | 670 | 10 | 10 | 2.5 | 15.3 | 0 | 4.9 | 310 | 1055 | 1.50 | 113 | 260 | 57 | 480 | 19 | 51 | 13 | 720 | 137 | 1 | 105 |
| 2 | 11 Sep 2007 | 2 | 20 | 6.94 | 450 | 10 | 130 | 4.5 | 16.7 | 5 | 4.2 | 9 | 2310 | 1.10 | 35 | 200 | 52 | 334 | 13.1 | 39.9 | 5.7 | 631 | 43 | 0.5 | 48 |
| 3A | 12 Sep 2007 | 2 | 20 | 6.2 | 580 | 10 | 5 | 3.5 | 15.5 | 45 | 11 | 78 | 6080 | 3.40 | 75 | 580 | 42 | 935 | 36.6 | 118 | 19 | 1640 | 92 | 0.5 | 168 |
| 3A | 25 Feb 2008 | 2 |  | 6.52 | 1500 | 5 | 10 | 32 | 24.4 | 0 | 40 | 160 | 11430 | 6.40 | 110 | 1400 | 41 | 1990 | 90.2 | 274 | 58.5 | 3410 | 134 | 0.5 | 391 |
| 3C | 25 Feb 2008 | 2 |  | 7.25 | 250 | 20 | 30 | 2 | 21.9 | 0 | 4.9 | 30 | 1943 | 1.10 | 40 | 200 | 62 | 312 | 12.9 | 40.8 | 7.4 | 543 | 49 | 0.5 | 31.7 |
| 4 | 11 Sep 2007 | 2 | 40 | 7.44 | 760 | 10 | 10 | 7.5 | 13.4 | 17.6 | 5.9 | 75 | 6110 | 3.30 | 83 | 570 | 45 | 926 | 35.8 | 117 | 18.3 | 1590 | 101 | 0.5 | 169 |
| 4 | 25 Feb 2008 | 2 |  | 7.04 | 400 | 10 | 5 | 5 | 31.3 | 0 | 2.9 | 8 | 3860 | 1.90 | 55 | 380 | 39 | 578 | 20.7 | 78.8 | 21.2 | 1040 | 67 | 0.5 | 52.9 |
| 5 | 13 Sep 2007 | 2 | 25 | 6.36 | 500 | 20 | 5 | 4.5 | 15.7 | 22 | 1.5 | 37 | 6910 | 3.70 | 70 | 690 | 56 | 1100 | 41.4 | 142 | 20.6 | 1980 | 85 | 0.5 | 167 |
| 5 | 26 Feb 2008 | 2 |  | 7.44 | 510 | 10 | 5 | 3.5 | 23.2 | 0 | 1.4 | 8 | 6840 | 3.50 | 120 | 700 | 44 | 1140 | 42.8 | 144 | 24.8 | 1910 | 146 | 0.5 | 75.7 |
| 6 | 13 Sep 2007 | 2 | 10 | 7.62 | 390 | 10 | 5 | 6 | 19.1 | 20 | 5.7 | 26 | 7400 | 4.10 | 88 | 710 | 54 | 1160 | 42.1 | 146 | 24.9 | 2090 | 107 | 0.5 | 177 |
| 16 | 23 Jul 1999 | 3 | 40 | 7.5 | 820 | 20 | 100 | 2 | 11.8 | 50 | 14 | 170 | 2820 | 1.30 | 93 | 230 | 34 | 441 | 19 | 45 | 13 | 700 | 113 | 1 | 65 |
| 7 | 13 Sep 2007 | 4 | 2 | 7.06 | 1100 | 20 | 5 | 10.5 | 20.8 | 0 | 1.6 | 180 | 7700 | 4.50 | 55 | 880 | 110 | 1120 | 52.1 | 181 | 26.2 | 2110 | 67 | 0.5 | 189 |
| 8 | 14 Sep 2007 | 4 | 5 | 6.67 | 1100 | 20 | 110 | 43.5 | 12.1 | 0 | 1.7 | 80 | 12880 | 8.00 | 50 | 1100 | 95 | 2060 | 44.8 | 244 | 42.1 | 3970 | 61 | 0.5 | 421 |
| 13 | 15 Sep 2007 | 5 | 30 | 8.38 | 660 | 20 | 5 | 7 | 19.1 | 0 | 0.25 | 26 | 7880 | 4.70 | 298 | 1100 | 47 | 1300 | 115 | 187 | 46.1 | 2290 | 308 | 27 | 378 |
| 14 | 10 Sep 2007 | 5 | 80 | 6.74 | 1100 | 50 | 5 | 6.5 | 20.9 | 0 | 7.2 | 88 | 2610 | 1.60 | 280 | 450 | 32 | 361 | 88.9 | 54.1 | 17.9 | 552 | 342 | 0.5 | 156 |
| 14 | 21 Jul 1999 | 5 | 120 | 7.55 | 680 | 30 | 10 | 2.5 | 17.3 | 0 | 1.3 | 93 | 3150 | 1.80 | 275 | 470 | 33 | 525 | 93 | 58 | 44 | 750 | 336 | 1 | 198 |
| 15 | 15 Sep 2007 | 5 | 40 | 9.72 | 1300 | 10 | 5 | 3.5 | 19.6 | 0 | 4.5 | 26 | 13090 | 8.80 | 80 | 1400 | 33 | 2210 | 140 | 266 | 77.2 | 3930 | 0.5 | 42 | 807 |
| 12A | 15 Sep 2007 | 6 | 5 | 7.98 | 450 | 30 | 5 | 4.5 | 25.5 | 0 | 0.25 | 8 | 21000 | 15 | 505 | 2800 | 110 | 3790 | 173 | 573 | 134 | 6550 | 360 | 0.5 | 839 |
| 12B | 15 Sep 2007 | 6 | 40 | 8.05 | 2300 | 40 | 5 | 5 | 24.7 | 0 | 29 | 17 | 180700 | 190 | 250 | 19000 | 38 | 51800 | 372 | 4450 | 1640 | 84800 | 305 | 0.5 | 7520 |
| 12C | 09 Oct 2008 | 6 | 10 | 7.26 | 3300 | 20 | 5 | 2.5 | 32.1 | 0 | 31 | 210 | 228300 | 320 | 180 | 30000 | - | 123000 | 764 | 6750 | 2450 | 208000 | 220 | 0.5 | 1200 |
| 12D | 21 Jul 1999 | 6 | 50 | 8 | 2200 | 10 | 10 | 3.5 | 18 | 0 | 3.9 | 2.5 | 170000 | 180 | 145 | 15000 | 6 | 69600 | 965 | 3000 | 1230 | 110000 | 177 | 1 | 6470 |

nine were fresh (0.68–2.6 g/L), 10 were hyposaline (3.4–15 g/L, most < 5 g/L) and three were hypersaline (180–320 g/L). The freshest sites were springs and spring-fed creeks (sites 1, 2, 9, 10 and 11) and the most saline was Hutt Lagoon (up to 320 g/L). The Hutt River was mostly low hyposaline (generally 3–7 g/L). In the three sites sampled in both spring 2007 and the following February, salinity was about the same in both seasons at site 5, lower in summer at site 4 and higher in summer at site 3A. Sites in the Hutt River catchment all had circumneutral pH (6.2–7.6) whereas pH in Hutt Lagoon catchment wetlands were mostly alkaline (6.7–9.7).

All wetlands were NaCl dominated, with order of milliequivalent cation dominance being $Na^{+}>Mg^{2+}>Ca^{2+}>K^{+}$ for all wetlands except for one sample from the main body of the Hutt Lagoon (site 12B) which had $Na^{+}>Mg^{2+}>K^{+}>Ca^{2+}$ and Utcha Swamp (site 14) which had $Na^{+}>Mg^{2+}= Ca^{2+}>K^{+}$. Sodium represented a particularly high proportion of anions in Hutt Lagoon (site 12B) and Yerina Spring (site 14), compensated for by lower $Mg^{2+}$ and $Ca^{2+}$.

Most sites had $Cl^{-}>SO_4^{2-}>HCO_3^{-}>CO_3^{2-}$ but three wetlands had $Cl^{-}>HCO_3^{-}>SO_4^{2-}>CO_3^{2-}$. The latter sites were the Hutt River downstream of Yarder Gully (site 3C), Hutt River south of Gregory Springs (site 5) in summer (but not spring) and Utcha Swamp (site 14). Utcha Swamp had particularly high percentage of $HCO_3^{-}$ (18 to 23%) which, combined with the relatively high percentage of $Ca^{2+}$ (14 to18%), probably reflects the limestone geology of the underlying aquifer (Arakel & Moulton 1986). Sulfate contributed relatively strongly (13–14 %) to anion composition at Yerina Spring (site 11), Utcha Swamp (site 14) and the sedge flats north of Hutt Lagoon (site 15).

Most sites had chlorophyll concentrations between 2 and 11 μg/L, the exceptions being Feast Soak (site 8) with 43.5 μg/L and Hutt River downstream of Yarder Gully confluence (site 3A) with 32 μg/L in summer (3.5 μg/L in spring). The other two sites which were sampled in both seasons had lower total chlorophyll concentrations in summer than in spring. Site 3A was also the only one of the three sites sampled in both seasons to have higher nitrogen concentration in summer. Nitrogen concentrations were mostly 300–900 μg/L, a few sites had 1000–1500 μg/L and three sites had nitrogen concentrations above 2000 μg/L (sites 3B, 11 and 12B). Site 3B also had 130 μg/L of phosphorus whereas phosphorus concentrations at the remaining sites were less than 50 μg/L.

### Invertebrate diversity

A total of 219 taxa were collected in the 2007/08 survey, bringing the total number of taxa from all sampling to 249 (Appendix 1). Most species (155) were insects, over half of which (85) were dipterans. Fifty species were crustaceans, primarily ostracods and copepods, with oligochaetes (12 species) and rotifers (14 species) the richest of the remaining groups. Richness in a sample varied from 10 in Hutt Lagoon in 1999 to 62 in Yerina Spring in 1999 and averaged 38.9 ± 2.7. Thirty-eight percent of species were recorded only in one sample, 69% were recorded in 3 or fewer samples and only 5% were present in more than half of the samples.

The Chao2 species richness estimator suggests regional richness is likely to be about 343 species (95% C.I. 304–410), suggesting the survey effort to date may have collected about two-thirds of the species present in the sampled wetlands. In the three sites sampled in both spring and summer, only about a third of species collected at each site occurred in both seasons. Sites 3A and 4 had almost the same richness in summer as in spring but in site 5 summer richness was lower than in spring. Of the 87 species that occurred in any of the four summer samples (above sites plus 3C) 16 were not recorded at any sites in spring, but most of these were singletons and not likely to be associated with summer conditions in particular.

### Invertebrate communities

The agglomerative clustering using average, complete and flexible linkage produced similarly structured dendrograms. The Hutt Lagoon samples (from sites 12A–D) always grouped together; sometimes with the sample from site 15 (the sedge flats north of Hutt Lagoon). Otherwise site 15 grouped with samples from sites 13 and 14 (which otherwise always formed a group on their own), usually as a sister group to the samples from sites 7 and 8. Remaining sites (all from the Hutt River catchment) generally formed two groups, one comprising samples from the main channel of the Hutt River (samples from sites 3A, 3C, 4, 5 and 6) and one with samples from the springs, spring-fed tributaries and the granite rock pools (from sites 1, 2, 3B, 9, 10 and 11). The first of these groups split into a group consisting of all of the samples collected in summer and one with all of the samples collected in spring. The sample from site 16 always clustered separately from other samples. The main deviation from the above clustering was that the average linkage method did not so clearly separate samples from the Hutt River channel from those of the springs and tributaries. Co-phenetic correlations for these dendrograms were between 0.86 and 0.92 suggesting that they represented original inter-sample distances very well. Simprof analyses suggested that all of the above groupings were significant. In the k-means (non-hierarchical) cluster analysis, the four Hutt Lagoon samples split into two groups: one with the two 2007 samples and one with the samples from 2008 and 1999. Samples from sites 13, 14 and 15 grouped together (as in some of the hierarchical analyses) but grouping of the Hutt River catchment samples did not neatly separate main channel from spring/tributary samples (as in the average linkage method). All samples from the main Hutt River channel sites grouped together, but this group included all three samples from Yarder Gully (sites 1, 2 and 16) and the 1999 sample from Yerina Spring (site 11). The remaining springs and tributaries formed two groups: samples from sites 7, 8 and 3B forming one group and those from sites 9, 10 and the 2007 sample from site 11 forming another. Based on these analyses we suggest six groupings of samples. In the descriptions of sample groups below, a species is considered to be strongly associated with the group if it occurred in more than half of the samples in the group and was twice as likely to be represented in the group as would be expected by chance.

## GROUP 1 FRESHWATER SPRINGS AND SPRING-FED CREEK

This group consists of seven samples, all from springs, spring-fed creeks or seepages (sites 1, 2, 3B, 9, 10 and 11), although only site 10 had significant flow at the time of sampling. Most sites in this group were fresh (< 2.6 g/L) but TDS at site 3B was 8.8 g/L. Water chemistry at site 3B was measured in a rock pool close to the river which possibly filled with hyposaline river water prior to sampling, whereas invertebrates were also collected from higher elevation pools filled from fresh bank-seepage. The fauna at this site seems to be a combination of salt-tolerant and salt-sensitive taxa, giving this site particularly high richness (60 taxa). That this site clustered with the more saline seepages (sites 7 and 8 in group 4) in some analyses indicates the duplex nature of its fauna. A total of 151 species were recorded from these samples (average 47 ± 4.2/sample), of which 47 were not found in samples from other cluster groups. Most of the latter were singleton records so their occurrence only in this group is perhaps a matter of chance, but some are species that tend to be associated with freshwater springs, swamps and seepages, such as the mosquito *Culiseta atra*, beetle *Helochares tenuistriatus* and dragonflies *Nannophya occidentalis*, *Archaeosynthemis occidentalis* and *Orthetrum pruinosum migratum*. Species strongly and disproportionately represented in these samples were the copepod *Paracyclops chiltoni*, odonates *Adversaeshna brevistyla* and *Ischnura aurora* and chironomids *Polypedilum* nr *convexum*, *Paralimnophyes pullulus*, *Paramerina levidensis*, *Cricotopus albitarsus* and *Alotanypus dalyupensis*.

## GROUP 2 HUTT RIVER CHANNEL

This group comprises all eight samples from the main channel of the Hutt River (sites 3A, 3C, 4, 5 and 6), though in some of the cluster analyses these were not clearly separated from samples in group 1. These sites were characterised by having flow in spring (but not in summer) and fresh to mildly hyposaline water (1.1–6.7 g/L, average 3.4). Total filterable nitrogen also tended to be lowest at these sites (mostly <600 ug/L). Samples from these sites contained 129 species, of which 32 (mostly singletons) occurred only in these sites. Average richness was 46 ± 2.7. Numerous species were strongly associated with this group, including the mayfly *Tasmanocoenis tillyardi*, gyrinid beetles, the blackfly *Simulium ornatipes*, ceratopogonids *Bezzia* spp. and *Monohelea* sp. 1, chironomids *Rheotanytarsus* sp., *Cladopelma curtivalva* and *Cryptochironomus grisiedorsum*, the caddisflies *Cheumatopsyche* AV2, *Oxyethira* sp. and *Acritoptila* sp. and the copepod *Onychocamptus bengalensis*. Many of these species are characteristic of flowing (or at least lotic) and/or hyposaline water. Some cluster analyses indicated that the four samples collected in late summer 2008 had a different composition from those collected in spring, but it is difficult to identify individual species responsible for this. *Thienemanniella* and *Harrisius* chironomids were present in four or five samples collected in spring but were absent in summer. By contrast, the copepods *Mesocyclops brooksi* and *Onychocamptus bengalensis* were much more common in summer. Such differential occurrences probably reflect the fact that all samples were collected in flowing water during spring but in still water in summer. Salinities were about the same in both seasons.

## GROUP 3 SITE 16 (LOWER YARDER GULLY SAMPLED IN 1999)

This sample consistently fell out as a sister sample to groups 1 and 2. The site was fresh (1.3 g/L) and flowing when sampled. Only five of the 38 species present were not collected in any other samples. These were the oligochaetes *Insulodrilus* cf. *lacustris* and *Dero furcata*, ostracod *Candonopsis tenuis* and chironomids *Ablabesmyia notabilis*, and Orthocladiinae 'SO3' sp. A, i.e. all species that tend to be associated with freshwater. This site clustered with groups 1 and 2 because it shared many of the freshwater and flowing water species with samples in those groups. However, this sample lacked a number of dipteran species that were very common in samples of groups 1 and 2 (*Chironomus* aff. *alternans*, *Procladius paludicola*, *Paramerina levidensis Tanytarsus fuscithorax/semibarbitarsus*, and *Culicoides* sp.).

## GROUP 4 SUB-SALINE SEEPAGES

This group consists of the two samples from Gregory Spring (site 7) and Feast Soak (site 8). These sites were shallow (~5 cm), hyposaline (4.5 and 8 g/L) and had higher chlorophyll (10.5 and 43.5 μg/L respectively) than all other sites except for 3B. Silica concentrations were also comparatively high (110 and 95 mg/L). These samples had 41 and 32 species respectively (58 combined), with only 15 collected from both. Species occurring in both sites but not present in other samples were the ostracods *Heterocypris* sp. and *Bennelongia* sp. 4, the copepods *Metacyclops* sp. 434 and the mosquito *Culex globocoxitus*. Other species of particular note are an undescribed *Austrotrombella* water mite (known only from a few other northern Wheatbelt sites), a possibly new *Arrenurus* water mite and some other taxa whose distributions are uncertain but which have rarely been recorded in the mid-west or Wheatbelt, such as Orthocladiinae sp. A, *Culex* sp. 3 and *Anopheles atratipes*.

## GROUP 5 LOW SALINITY WETLANDS NORTH OF HUTT LAGOON

This group consists of all samples from the fresh to hyposaline wetlands in the Hutt Lagoon Catchment (sites 13 to 15). Utcha Swamp was fresh (1.8 in 1999 and 1.6 g/L in 2007) whereas sites 13 and 15 were hyposaline (4.7 and 8.8 g/L). These samples contained 81 species (27–45 per sample), including a number of widespread species which were present in three or four of these samples but otherwise comparatively rare. The latter were the chironomids *Dicrotendipes conjunctus* and *Procladius villosimanus*, the beetle *Hyphydrus elegans*, hemipterans *Agraptocorixa eurynome* and *Anisops elstoni* and the ostracod *Kennethia cristata*. These tend to occupy lentic rather than lotic habitats.

## GROUP 6 HUTT LAGOON SITES

This group consists of the four Hutt Lagoon samples from sites 12A–D. Thirty-two species were present in these samples and sample richness varied between 10 and 18. Composition was highly variable, with only three species present in more than two samples (*Austrochiltonia* *subtenuis*, *Artemia* sp. and *Tanytarsus barbitarsus*). These four samples were from the highest salinity sites, although 12A (seepage area on the edge of the lagoon) had much lower salinity (15 g/L) than the main lagoon (sites 12B–D with salinity 180 to 320 g/L).

SUMMARY

In a three-dimensional nMDS ordination (Figure 2) these six groups of samples are reasonably well separated from each other. Group 6 (Hutt Lagoon samples) are well separated from the remaining (fresh to hyposaline) samples and groups 5 and 6 (all Hutt Lagoon catchment samples) are more dispersed in the ordination than the other groups, reflecting their more heterogeneous composition. Remaining groups are in close proximity but with little or no overlap.

### Complementarity

A premise of the Walshe *et al.* (2004) analysis was that the catchments selected would be complementary in terms of their biodiversity assets. This was tested in a 2D ordination (stress = 0.19) of invertebrate communities from the Hutt wetlands and wetlands in most of the Recovery Catchments (Bryde, Drummond, Toolibin, Buntine–Marchagee and Warden). The Muir–Unicup Recovery Catchment has also been surveyed for invertebrates but the data are not yet available: however, considering its position in the higher rainfall southwest, that catchment is likely to have a very different fauna to the other catchments. After removing or merging taxa to make the datasets compatible, a total of 419 taxa remained. In the ordination (Figure 3) the Hutt samples occupied areas adjacent to, but mostly not overlapping, samples from the other catchments. This indicates that the Hutt catchments support an invertebrate fauna not represented in the other catchments. The clear exception is Hutt Lagoon (the four red dots towards the right in Figure 3) which were positioned in the same area as the largely saline Buntine–Marchagee wetlands. The similarity between Hutt Lagoon and the saline Buntine–Marchagee communities was probably due to shared presence of a few common halophilic species such as *Artemia* and *Australocypris insularis*. Some of the other catchments seem to overlap with one another in Figure 3 but in a 3D ordination (not shown) all are reasonably well separated. A Permanova analysis (to test whether the Hutt fauna differed from the faunas of other recovery catchment) was not performed because the data from different catchments are unequally dispersed within ordination space (tested using Permdisp in Primer).

## DISCUSSION

### Invertebrate diversity and composition

The invertebrate richness estimated for the region by the Chao2 estimator (about 340 species) suggests the survey effort to date has revealed about 73% of the aquatic invertebrate fauna potentially inhabiting the particular wetlands sampled in the region. This is on par with other aquatic invertebrate survey projects in Western Australia (Pinder *et al.* 2004, 2010a). Further survey effort would help to describe invertebrate diversity and habitat associations more thoroughly in these catchments,

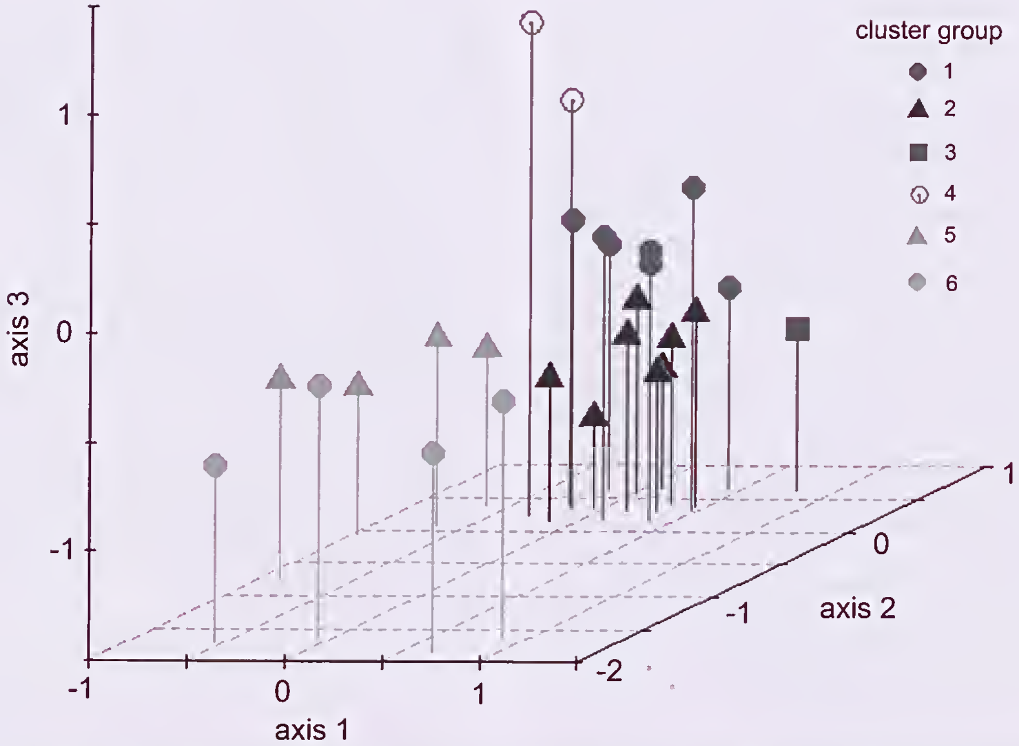


Figure 2. Three-dimensional nMDS ordination (stress = 0.1) of wetlands based on aquatic invertebrate community composition, showing the six groups derived from the cluster analysis.

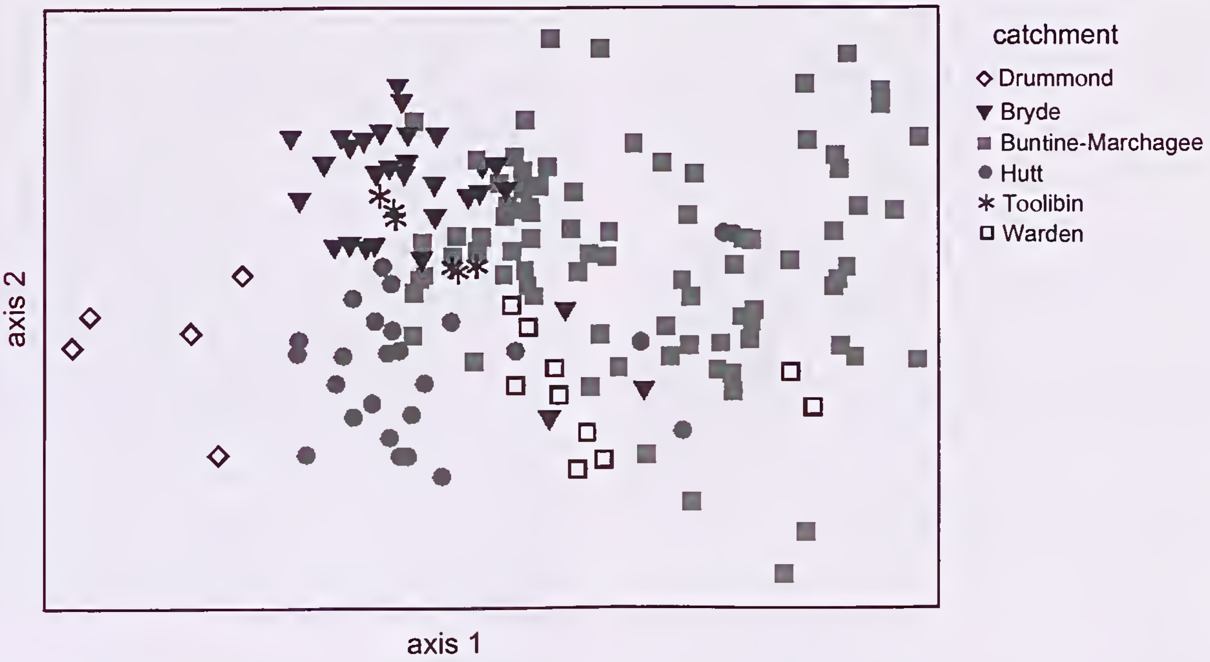


**Figure 3.** Two-dimensional nMDS ordination (stress = 0.19) of wetlands from the Hutt catchments and Natural Diversity Recovery Catchments based on aquatic invertebrate community composition.

particularly if the sampling gaps are filled. That most species occurred infrequently probably reflects the wide range of wetland types compared to the number of sites sampled.

The 249 taxa collected from the Hutt catchments is about a fifth of the total number of species collected from the Wheatbelt region (Cale *et al.* 2004; Jones *et al.* 2009; Pinder *et al.* 2004 and unpublished data). The average richness per sample in the Hutt catchments (38.9) was very similar to the average richness (40.1) for all Wheatbelt wetlands sampled by Pinder *et al.* (2004). However, richness is strongly correlated with salinity in the Wheatbelt region (Pinder *et al.* 2005), so comparisons of richness need to take that into account. When plotted against salinity, sample richness in the Hutt catchments' fresh and hyposaline wetlands appears somewhat lower than would be predicted from salinity alone (Figure 4). This may have been because many of the freshwater sites were small springs, seepages and creeks which tend to have lower richness (for a given salinity) than the larger lentic wetlands that predominate in the Wheatbelt survey dataset.

The catchment and sample richness for the Hutt is similar to that recorded in some other small catchments in the inland southwest that have been sampled using comparable methods and taxonomic scope and

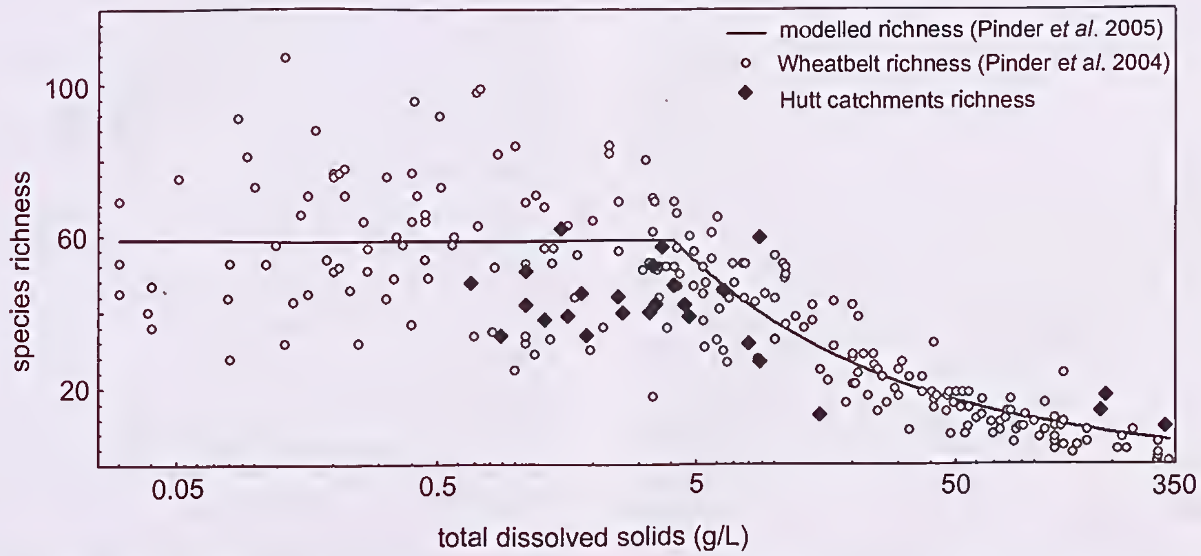


**Figure 4.** Total dissolved solids *vs* richness of aquatic invertebrate communities in Hutt wetlands and in wetlands sampled for the biological survey of the Southwest Agricultural Zone (Pinder *et al.* 2004), with the richness-salinity model from Pinder *et al.* (2005).

resolution. Cale (2008) and Cale *et al.* (2004), supplemented by unpublished data held by the Department of Environment & Conservation (DEC), recorded 240 taxa in 29 samples from seven mostly hyposaline to saline wetlands in the Lake Bryde Recovery Catchment. The average richness per sample in those wetlands was 42 ± 2.5, about the same as that in samples of the Hutt catchments.

In 21 wetlands in the Buntine–Marchagee Recovery Catchment (Aquatic Research Laboratory 2009 and reports therein) collected 223 taxa in 87 samples collected over five years. Average richness was only 20 ± 1.4/sample but these wetlands were almost all saline. Species in common with the Hutt catchments were mostly very widespread and salt-tolerant, but include *Polypedilum leei*, a northern element (see Biogeography below) and *Limnocythere porphretica*, which is widespread in the southwest and Carnarvon Basin (Halse *et al.* 2000a) but uncommon compared to its congeners.

Several freshwater springs at the headwaters of the Arrowsmith River in the northern Wheatbelt, supporting a listed threatened ecological community (Rees & Broun 2005), were sampled by Pinder& Leung (2010 and reports therein). These have at least 176 species, with an average richness of 37 ± 4 per spring. Species in common between these springs and the Hutt catchments include some that are relatively rare in the Wheatbelt and tend to be found primarily in fresh and permanently moist habitats, such as the mosquitoes *Culiseta atra* and *Anopheles atratipes*, odonates *Archaeosynthemis occidentalis* and *Archiargiolests pusillus* and the water mite *Austrotrombella* n. sp.

Further south, the Muir–Unicup Recovery Catchment has a much richer fauna of around 400 species [unpubl. data from DEC, A Storey (University of Western Australia) and R Sheil (University of Adelaide)] but this higher richness reflects the much larger number of wetlands sampled (53) and that most of them are fresh. Average sample richness was about 47 species (Storey 1998). Unlike other recovery catchments, the Muir–Unicup fauna would include most of those species listed above as 'southwest' species whose Hutt populations are northern outliers.

Virtually all of the Hutt catchments' species are known from elsewhere (see Biogeography below) and it is unlikely that any are locally endemic. Between 21 and 36% of the Hutt catchments' fauna were present in each of the catchments mentioned above and at least 77% of the Hutt fauna occurs within one or more of them. However, this is based solely on presence/absence and would be true of almost all other catchments with a similar range of aquatic habitats in the southwest. Simple comparisons of species lists do not account for different probabilities of occurrence across landscapes. Our results indicate that aquatic invertebrate communities occurring in individual Hutt catchment wetlands are dissimilar in composition to those in established recovery catchments. Management of the Hutt wetlands for conservation would therefore be likely to protect a fauna that would not be as well represented elsewhere in the agricultural southwest.

The Walshe *et al.* (2004) analysis used aquatic species assemblages (waterbirds, aquatic invertebrates and aquatic flora) identified by Halse *et al.*(2004). The analysis suggested that assemblages 2 and 4 of Halse *et al.* (2004) were likely to be particularly well represented in the Hutt catchments but under-represented across the selected catchments overall, compared to species richness targets. Assemblage 2 included 54 invertebrate species found mostly in association with hyposaline water. Of these, 23 have now been recorded in the Hutt catchments. Average richness of assemblage 2 across the wider Wheatbelt (from the Wheatbelt survey excluding Hutt sites) was 1.5 ± 2 per sample whereas in the Hutt catchments there were 3.3 ± 0.5. Assemblage 4 included 38 invertebrates associated with fresh to hyposaline flowing water, especially in sites along the eastern slopes of the Darling Range. Of these, 14 have now been recorded in Hutt wetlands. Average richness of assemblage 4 across the wider Wheatbelt was 1 ± 0.2 per sample, whereas in the Hutt catchments there were 2.5 ± 0.5 per sample. These figures confirm that assemblages 2 and 4 are better represented in Hutt wetlands than in the wider Wheatbelt, but this was not the case for any of the other Halse *et al.* (2004) assemblages.

## Biogeography

Most species recorded in the Hutt catchments are common in southwestern or southern Australia or even continentally, but some are southwest endemics and others have primarily northern and/or inland distributions.

A few of the species that are endemic to the southwest are much more commonly encountered in higher rainfall parts of the region and appear to be rare north of Perth. These are listed in Table 3, which also has notes on other northern records and wider distributions. Their occurrence in the Hutt River catchment is probably facilitated by the presence of permanent low-salinity water provided by the springs. Most of these, and numerous additional species with similar patterns of distribution, have been collected in fresh, permanently moist, organic mound springs near the town of Three Springs, 200 km north-northeast of Perth (Pinder & Leung 2010). Such species have been absent from other wetlands surveyed in the northern Wheatbelt and Mid-west (Aquatic Research Laboratory 2009; Jones *et al.* 2009), including from fresh to mildly saline springs near Jurien sampled by Pinder & Quinlan (2012). This highlights the importance of the Three Springs and Hutt River springs in maintaining this component of aquatic diversity in the Mid-west.

Numerous species have primarily northern Australian distributions, some of which have not previously been recorded this far south and probably close to their southern limits in the Hutt catchments (Table 3). These mainly occurred in wetlands of the Hutt Lagoon catchment (in contrast to the southern endemics which primarily occurred in the Hutt River catchment). An additional 27 northern or northern/inland species were recorded by Pinder *et al.* (2004) in the Eneabba to Murchison River region. These were mostly rotifers such as *Lecane aculeata, Lecane papuana* and *Trichocerca chattoni* or beetles such as *Batrachomatus wingi* and *Hydrochus lateviridus*. Others included the mosquito *Culex palpalis*, ostracod *Zonocypretta kalimna* and dragonfly *Austrogomphus gordoni*.

**Table 3** Occurrence of southwestern endemic species and northern Australian species collected in Hutt wetlands

| | Species | Occurrence in the present survey | Habitat and distribution |
|---|---|---|---|
| **Southwestern endemic species** | | | |
| Aquatic earthworms | *Ainudrilus nharna* | sites 4 & 10 | A mildly salt tolerant species common in the south-west, including the southern and central Wheatbelt (Cale *et al.* 2004; Pinder *et al.* 2004), Only other records north of Toodyay are claypans in Drummond Nature Reserve (Cale 2005). |
| Mosquitoes | *Culiseta atra* and *Anopheles atratipes* | sites 1 & 7 | Tend to inhabit permanent coloured freshwater swamps with decaying leaf litter (Liehne 1991). Rarely recorded north of Perth. Both also recorded at organic mound springs south-west of Three Springs (Pinder & Leung 2010). |
| Dragonflies | *Archaeosynthemis occidentalis* | site 1 | Moderately common in permanent freshwater streams and wetlands south of Perth (Sutcliffe 2003). Also recorded in the Three Springs mound springs (Pinder & Leung 2010). |
| | *Nannophya dalei* | site 11 | Inhabits boggy freshwater seepages and swamps of the south-west and appears to be rare even south of Perth (Sutcliffe 2003). |
| Diptera | Orthocladinae 'DEC sp. I' | sites 1, 8 & 11 | Rare, in fresh to slightly saline swamps in the south-west. Otherwise only known from Three Springs mound springs in the mid-west (Pinder & Leung 2010). |
| | *Harrissius* sp. | sites 2, 3A, 4, 5 and 9 | *Harrisius* are common in streams and rivers of the Darling Range and further south. Otherwise only known from Three Springs mound springs in the mid-west (Pinder & Leung 2010). |
| | *Tanytarsus palmatus* | sites 1,2,5 & 11 | Widespread in streams in the south-west. |
| **Northern species** | | | |
| Beetles | *Megaporus ruficeps* | site 3B | Common in wetlands and rivers across northern Australia, but not recorded in southern Carnarvon Basin by Halse *et al.* (2000). Also recorded in a spring near Jurien (Pinder & Quinlan 2012). |
| | *Neohydrocoptus subfasciatus* | site 14 | Common in wetlands and rivers across northern Australia but not recorded in southern Carnarvon Basin by Halse *et al.* (2000). |
| | *Hydroglyphus leai* | sites 12A & 13 | Common in wetlands and rivers across northern Australia extending into the southern Carnarvon Basin (Halse *et al.* 2000) and mid-west (Daniel *et al.* 2009). |
| Water bugs | *Anisops nasuta* | site 13 | Common in wetlands and rivers across northern and inland Australia, including the Carnarvon Basin, but rare further south. Also recorded in a spring near Jurien (Pinder & Quinlan 2012). |
| | *Laccotrephes tristis* | sites 1 & 5 | Common in wetlands and rivers across northern Australia but rarely collected in south-western Australia. Not recorded in southern Carnarvon Basin by Halse et al. (2000). |
| | *Paraplea* sp. | sites 13 & 14 | Probably an undescribed species common at least in north-western Australia. Pleids uncommon in southern Western Australia but a few records listed by Aquatic Research Laboratory (2009) and Pinder *et al.* (2004). |
| Dragonflies | *Orthetrum pruinosum migratum* | site 1 | Common in wetlands (especially springs) across northern Australia but not recorded in southern Carnarvon Basin by Halse *et al.* (2000). |
| Rotifers | *Lecane grandis* | site 12D | A northern Australian halophilic rotifer (R.J. Shiel, University of Adelaide pers. comm.), not recorded south of Hutt Lagoon in Western Australia. |
| Diptera | *Polypedilum leei* | site 5 | A northern/inland chironomid (Cranston 2000) of wetlands and rivers that has been occasionally recorded in the Wheatbelt as far south as the Avon River, e.g. Aquatic Research Laboratory (2009) and Pinder (2009). |

From a conservation perspective, there are two ways of considering the northern and southern species towards the edges of their ranges. It could be argued that populations of these species may be at the limits of their ecological tolerances and that their conservation is likely to be more efficiently achieved in regions with more optimal environmental conditions. Thus, the northern species are more likely to persist in the Pilbara, with less active conservation effort than might be required to preserve them on the edge of their range. An alternative view is that transitional zones might be important in allowing species to cope with climate-change through migration and so suitable habitat should be maintained at and beyond the edges of current ranges. Furthermore, populations on the extremes of species' ranges may have genetic divergence/cryptic speciation (Thompson & Rich 2011) and/or adaptive resilience (including to changes in climate) not developed in populations in more benign parts of their range (Sexton *et al.* 2009). In any case, maintaining regional diversity means addressing the conservation needs of these components of the fauna.

An aquatic bio-regionalisation of Western Australia is yet to be produced, although there are enough data accumulating to begin such an analysis. An analysis of Freshwater Ecoregions of the World (FEOW) divided Western Australia into five regions, largely based on aquatic vertebrate species distributions (Unmack 2001; http://www.feow.org). The 'South-western Australian' and 'Paleo' FEOWs are divided at about the Arrowsmith River, which is close to the boundary (about the Irwin River) of the Geraldton Hills and Lesueur Sandplain terrestrial IBRA subregions (Australian Government 2004). These rivers lie within the northwest coastal extent of a broad zone of transition between a mesic-adapted southwest biota and a xeric-adapted northern/inland biota (Hopper 1979). Along the southeastern edge of this zone, Stewart (2009) identified a biogeographic divide along the south coast of Western Australia, distinguishing invertebrate faunas of fresher western rivers from those of more saline eastern rivers. The co-occurrence of northern and southwestern invertebrate species highlights the lower mid-west region as a zone of aquatic faunal transition.

A few species are notable for their apparent rarity. The oligochaete *Pristina sima*, recorded at sites 3 and 11, has previously been collected only from a spring in the eastern Pilbara region of Western Australia and from Boomerang Cave and Ellen Brook Spring near Perth. An undescribed *Austrotrombella* water mite (one of only two in the genus) from site 7 has otherwise been collected only from two streams south of Geraldton (Pinder *et al.* 2004) and from the Three Springs mound springs (Pinder & Leung 2010). Other possibly rare or restricted species are informally named so it is difficult to identify records in other published studies. Thus, some of the dipterans (*Culex* 'DEC sp. 3', *Aedes* nr *camptorynchus* and *Forcipomyia* spp.), the water mite *Arrenurus* sp. 25 and the copepod *Nitocra* sp. 3 have rarely or never been collected in the many other DEC projects.

Three microcrustaceans of marine affinity (copepods Lourinidae sp. and *Robertsonia* sp. and the ostracod *Paradoxostoma* sp.) occurred in Hutt Lagoon and may be related to congeners found in Lake McLeod, another large coastal lagoon surveyed by Halse *et al.* (2000a) and Russell (2004). They have not otherwise been recorded in inland waters of Western Australia, though there are marine species of these genera known from Australia.

Three introduced species were recorded. *Cherax caini* (non-hairy marron) and *Cherax destructor* (yabbie) are both common in the lower Hutt River and *C. caini* was collected in Yarder Gully. *Artemia* brine shrimp are introduced and at least one species (*Artemia parthenogenetica*) is an invasive species in Australia, with the potential to replace native *Parartemia* species in some Australian salt lakes (McMaster *et al.* 2007). However, the unidentified *Artemia* in Hutt Lagoon has now been present for several decades and is unlikely to have further ecological effects *in situ*. There is no evidence that *Parartemia* were ever present.

### Conservation

The main channel of the Hutt River retains significant riparian vegetation and a foreshore condition assessment reported moderate to good condition for most if its length (Department of Environment 2005). There is also significantly more uncleared land away from the channel in the lower to middle parts of the catchment than many other rivers in the region and sections of the lower to middle channel are also heavily vegetated. The riparian and in-stream vegetation contribute to aquatic invertebrate habitat diversity and a quarter of all species in Appendix 1 were collected only in the main channel of the Hutt River, so it has significant value in terms of maintaining diversity in the catchment. However, the river is secondarily saline and analyses by Pinder *et al.* (2005) suggested that many freshwater species would have disappeared from the river. Further salinisation is a major threat to the river and this could occur as a result of greater salt load from the upper catchment or through reduced dilution by the freshwater springs and spring-fed tributaries. Management of salinity in the eastern part of the Hutt River catchment is therefore likely to have significant benefits for the lower parts of the Hutt River. Concentrations of nitrates and total filterable phosphorus were below interim guideline values for southwestern Australian lowland rivers (ANZECC & ARMCANZ 2000) but are undoubtedly elevated compared to pre-European times. Total filterable nitrogen concentrations were comparatively high at sites 3A and 3B (1500 and 3600 µg/L respectively, above the guideline of 1200 µg/L for total nitrogen in southwest rivers) and these were associated with elevated chlorophyll concentrations (32 µg/L at site 3A in summer). The somewhat different composition of the fauna of the river when it is flowing (in spring) versus when it is present as standing pools, suggests the river's full invertebrate component requires a seasonal flow regime.

Springs and spring-fed creeks (sample groups 1, 3 and 4) play an important role in reducing salinities in the Hutt River, but they also have significant value in their own right as remaining freshwater habitats supporting species with limited tolerance to elevated salinity. It is in the springs and spring-fed tributaries of the Hutt River that most of the invertebrate diversity resides, including 60 species not found in other wetland types and most of the rarer species and those southwestern endemics whose Hutt populations are northern outliers. For the southwestern endemics, at least, these springs provide permanently moist freshwater refugia in a dry (and drying) region. For these reasons, maintaining water quality and flow in the springs should be a priority and would have further benefit to the Hutt River by ameliorating secondary salinity.

The Hutt Lagoon is one of only a few such coastal salt lakes (sometimes known as birridas) in Western Australia. Similar wetlands include the Leeman Lagoons 200 km south of the Hutt River (Susac *et al.* 2009), Lake McLeod near Carnarvon (Halse *et al.* 2000a) and Mandora Marsh east of Port Hedland (Storey *et al.* 2011), but these wetlands have quite different hydrogeochemistry and faunas. Other coastal lagoons further south in the State, such as the Yalgorup lakes and Leschenault Inlet have also very different biotas (DEC unpubl. data). Inland saline playas also seem to have very different faunas (Pinder *et al.* 2004; Timms 2009; Williams *et al.* 1998). The locally unique element of the Hutt Lagoon fauna is the few crustaceans of marine affinity, possibly shared with at least Lake McLeod. Hutt Lagoon is intermittently used by large numbers of migratory shorebirds, though the extent of this depends on availability of other wetlands in the northwest. Conservation management issues are the beta-carotene production ponds and an existing garnet mine northwest of the lagoon, but neither of these are much of a threat to the lagoon invertebrate fauna as currently managed.

The area to the north of Hutt Lagoon has a diverse suite of wetlands still in reasonable condition, such as Utcha Swamp (site 14) and the *Baumea*/*Cyperus* fringed swamp (site 13). Utcha Swamp could be considered a significant wetland in the region because it is a vegetated freshwater lentic wetland in an area where such waters are rare, although it is being taken over by *Typha domingensis*, significantly reducing the area of open water and submerged macrophytes and therefore invertebrate habitat diversity. Utcha Swamp was the only locality for the undescribed *Arrenurus* sp. 25 water mite and the northern beetle *Neohydrocoptus subfasciatus*, but otherwise these wetlands supported very few species not present in other wetlands in the catchments. Most of the fauna of these wetlands comprises very widespread species.

In summary, the Hutt catchments contain a variety of wetland types supporting an aquatic invertebrate fauna that is at least as rich as others that have been surveyed with similar intensity in the agricultural zone of southwestern Australia. Moreover, we suggest that efforts to manage these catchments for conservation would protect an element of the fauna not as well represented in other catchments intensively managed for conservation.

## ACKNOWLEDGEMENTS

This project was facilitated by the Department of Environment and Conservation's (DEC) Natural Diversity Recovery Catchments program, via the Buntine Marchagee NDRC. Funding was provided by State and Australian Governments, and administered by the Northern Agricultural Catchments Council. Additional funds to assist in preparing this paper were provided by the State Salinity Strategy via DEC's Mid-west region. Thanks to Rowan Dawson from DEC's Geraldton Office and Margi Wier from Greening Australia for assisting with site selection and facilitating field work. Cara Francis identified the chironomids, Brian Timms (University of New South Wales) identified the brine shrimp and Russell Shiel (University of Adelaide) identified the cladocerans and rotifers. Andrew Storey (University of Western Australia) provided invertebrate data for Muir–Unicup wetlands. Stuart Halse (Bennelongia Pty Ltd) provided advice on ostracod identifications. Thanks to Leonie Box, Frank Mauger and Tracey Leach for allowing us access to their properties.

## REFERENCES

Aquatic Research Laboratory 2009. Buntine Marchagee Natural Diversity Recovery Catchment (BMNDRC). Wetland invertebrate fauna sampling: 2008. Aquatic Research Laboratory, University of Western Australia Report to the Department of Environment and Conservation, Perth (unpubl.).

Arakel A & Moulton T 1986. Hydrochemistry of surficial brines in Hutt Lagoon, Western Australia. *Palaeogeography, Palaeoclimatology, Palaeoecology* 54, 261–282.

ANZECC (Australian and New Zealand Environment and Conservation Council) & ARMCANZ (Agriculture and Resource Management Council of Australia and New Zealand) 2000. Australian and New Zealand guidelines for fresh and marine water quality. ANZECC & ARMCANZ, Canberra.

Department of Sustainability, Environment, Water, Populations & Communities 2004. Interim biogeographic regionalisation of Australia v6.1. <http://www.environment.gov.au/parks/nrs/science/bioregion-framework/ibra/index.html>(accessed 30 June 2011).

Cale D J 2005. Drummond natural diversity recovery catchment aquatic invertebrate survey. Department of Conservation and Land Management, Perth, Report (unpubl.).

Cale D J 2008. Wetland survey of the Lake Bryde Natural Diversity Recovery Catchment: waterbirds, aquatic invertebrates and water chemistry. Department of Environment and Conservation, Perth, Report (unpubl.).

Cale D J, Halse S A & Walker C D 2004. Wetland monitoring in the Wheatbelt of south-west Western Australia: site descriptions, waterbird, aquatic invertebrate and groundwater data. *Conservation Science Western Australia* **5**, 20–136.

Chao A 1987. Estimating the population size for capture–recapture data with unequal catchability. *Biometrics* **43**, 783–791.

Colwell R K 2006. EstimateS: statistical estimation of species richness and shared species from samples, Version 8. <http://viceroy.eeb.uconn.edu/estimates>.

Commonwealth of Australia and the State of Western Australia 1999. Regional Forest Agreement for the South-west Forest Region of Western Australia between the Commonwealth of Australia & the State of Western Australia, Canberra.

Cranston P S 2000. Electronic guide to the Chironomidae of Australia (http://entomology.ucdavis.edu/chiropage/index.html). Accessed 28 Feb 2000.

Daniel G, Kern S & Pinder A 2009. Resource condition report for a significant Western Australian wetland: wetlands of the Muggon ex-Pastoral Lease. Department of Environment and Conservation, Perth, Western Australia.

Davis J A, Rosich R S, Bradley J S, Growns J E, Schmidt L G & Cheal F 1993. Wetlands of the Swan Coastal Plain: wetland classification on the basis of water quality and invertebrate community data. Water Authority of Western Australia, Perth.

Department of Environment 2005. Hutt River foreshore assessment. Department of Environment, Perth.

Department of Environment and Conservation 2006. Buntine–Marchagee Natural Diversity Recovery Catchment Recovery Plan: 2007—2027. Conservation Commission Western Australia and Department of Environment and Conservation, Perth.

Desmond A & Chant A 2002. Geraldton Sandplains 2 (GS2 - Geraldton Hills subregion). *In*: May J E & McKenzie N L (eds) *A biodiversity audit of Western Australia's 53 biogeographical subregions in 2002*, pp. 265–292. Department of Conservation and Land Management, Perth.

Edward D H D, Gazey P & Davies P M 1994. Invertebrate community structure related to physico-chemical parameters of permanent lakes of the south coast of Western Australia. *Journal of the Royal Society of Western Australia* **77**, 51–63.

Environment Australia 2001. *A directory of important wetlands in Australia* (3rd edition). Environment Australia, Canberra.

Halse S A, Lyons M N, Pinder A M & Shiel R J 2004. Biodiversity patterns and their conservation in wetlands of the Western Australian Wheatbelt. *Records of the Western Australian Museum Supplement* **67**, 337–364.

Halse S A, Pearson G P, McRae J M & Shiel R J 2000b. Monitoring aquatic invertebrates and waterbirds at Toolibin and Walbyring Lakes in the Western Australian Wheatbelt. *Journal of the Royal Society of Western Australia* **83**, 17–28.

Halse S A, Shiel R J & Pearson G B 1996. Waterbirds and aquatic invertebrates of swamps on the Victoria–Bonaparte mudflat, northern Western Australia. *Journal of the Royal Society of Western Australia* **79**, 217–224.

Halse S A, Shiel R J, Storey A W, Edward D H D, Lansbury I, Cale D J & Harvey M S 2000a. Aquatic invertebrates and waterbirds of wetlands and rivers of the southern Carnarvon Basin, Western Australia. *Records of the Western Australian Museum Supplement* **61**, 217–265.

Halse S, Shiel R J & Williams W D 1998. Aquatic invertebrates of Lake Gregory, northwestern Australia, in relation to salinity and ionic composition. *Hydrobiologia* **381**, 15–29.

Hopper S D 1979. Biogeographical aspects of speciation in the south-west Australian flora. *Annual Review of Ecology and Systematics* **10**, 399–422.

Horwitz P 1997. Comparative endemism and richness of the aquatic invertebrate fauna in peatlands and shrublands of far south-western Australia. *Memoirs of the Museum of Victoria* **56**, 313–321.

Jones S, Collins M, Francis C & Halliday D 2009. Stage 3 evaluations of 28 wetlands in the Avon Natural Resource Management Region. Department of Environment and Conservation, Perth.

Keighery G J, Halse S A, Harvey M S & McKenzie N L (Editors) 2004. A biodiversity survey of the Western Australian Agricultural Zone. *Records of the Western Australian Museum Supplement* **67**.

Legendre P & Legendre L 1998. *Numerical Ecology*. Elsevier, Amsterdam.

Liehne P F S 1991. An atlas of the mosquitoes of Western Australia. Health Department of Western Australia, Perth.

Lyons M N, Gibson N, Keighery G J & Lyons S D 2004. Wetland flora and vegetation of the Western Australian Wheatbelt. *Records of the Western Australian Museum Supplement* **67**, 39–89.

Maechler M, Rousseeuw P, Struyf A & Hubert M 2007. Cluster: cluster analysis basics and extensions package for R, v1.14.0 <http://cran.r-project.org/web/packages/cluster/citation.html>.

McKenzie K G, Halse S A & Gibson N 2000. Some gaps in the reserve system of the southern Carnarvon Basin, Western Australia. *Records of the Western Australian Museum Supplement* **61**, 547–567.

McMaster K, Savage A, Finston T, Johnson M & Knott B 2007. The recent spread of *Artemia parthenogenetica* in Western Australia. *Hydrobiologia* **576**, 39–48.

Nowicki A, Pinder A, Kern S & Daniel G 2009. Resource condition report for a significant Western Australian wetland: Hutt Lagoon. Department of Environment and Conservation, Perth.

Oksanen J, Kindt R, Legendre P, O'Hara R, Simpson G L, Solymos P, Stevens M H H & Wagner H 2008. Vegan: community ecology package for R, v1.15 <http://vegan.r-forge.r-project.org/>.

Pinder A 2001. Notes on the diversity and distribution of Australia Naididae and Phreodrilidae (Oligochaeta: Annelida). *Hydrobiologia* **463**, 49–64.

Pinder A M 2009. Aquatic invertebrate communities in Avon and Dale river pools. Department of Environment and Conservation, Perth, Report (unpubl.).

Pinder A M & Leung A E 2010. Report on the August 2008 sampling of the aquatic invertebrate assemblages of mound springs of the Three Springs Area Threatened Ecological Community. Department of Environment and Conservation, Perth, Report (unpubl.).

Pinder A M, Leung A E, Cale D J & Halse S A 2010b. Waterbird and invertebrate monitoring of the Warden and Gore Wetlands in November 2009 and February 2010. Department of Environment and Conservation, Perth.

Pinder A M, Halse S A, McRae J M & Shiel R J 2004. Aquatic invertebrate assemblages of wetlands and rivers in the Wheatbelt region of Western Australia. *Records of the Western Australian Museum Supplement* **67**, 7–37.

Pinder A M, Halse S A, McRae J M & Shiel R J 2005. Occurrence of aquatic invertebrates of the Wheatbelt region of Western Australia in relation to salinity. *Hydrobiologia* **543**, 1–24.

Pinder A M, Halse S A, Shiel R J & McRae J M 2010a. An arid zone awash with diversity: patterns in the distribution of aquatic invertebrates in the Pilbara region of Western Australia. *Records of the Western Australian Museum Supplement* **78**, 205–246.

Pinder A M & Quinlan K 2012. Aquatic invertebrate communities of selected springs in the Jurien (Cervantes to Coolimba) region. Interim report to Department of Water. Department of Environment and Conservation, Perth.

Primer-E Ltd 2008. Primer v6.1.11. Primer-E Ltd, Plymouth, United Kingdom.

Pusey B J & Edward D H 1990. Limnology of the southern acid peatflats, south-western Australia. *Journal of the Royal Society of Western Australia* **73**, 29–46.

R Development Core Team 2011. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna.

Rees R & Broun G 2005. Assemblages of organic mound springs of the Three Springs Area: Interim Recovery Plan 2005–2010. Interim Recovery Plan 196. Department of Environment and Conservation, Perth.

Russell P 2004. Geological and geomorphological features and evolution of the Lake Macleod–Ningaloo–Cape Range–Exmouth Gulf area, Western Australia, including an assessment of values against World Heritage List Criteria. Report prepared for the Department of Conservation and Land Management, Perth.

Sexton J P, McIntyre P J, Angert A L & Rice K J 2009. Evolution and ecology of species range limits. *Annual Review of Ecology and Systematics* **40**, 415–436.

Stewart B A 2009. Two aquatic bioregions proposed for the South Coast region, Western Australia. *Journal of the Royal Society of Western Australia* **92**, 277–287.

Storey A W 1998. Assessment of the nature conservation values of the Byenup–Muir Peat Swamp System, south-western Australia: physico-chemistry, aquatic macroinvertebrates and fishes. Report for the Department of Conservation and

Land Management. Wetland Research and Management, Perth (unpubl.).

Storey A W, Halse S A & Shiel R J 1993. Aquatic invertebrate fauna of the Two Peoples Bay area, south-western Australia. *Journal of the Royal Society of Western Australia* **76**, 25–32.

Storey A W, Halse S A & Shiel R J 2011. Aquatic fauna and water chemistry of the mound springs and wetlands of Mandora Marsh, north-western Australia. *Journal of the Royal Society of Western Australia* **94**, 419–437.

Susac R, Kern S, Pinder A & Daniel G 2009. Resource condition report for a significant Western Australian Wetland: Leeman Lagoon. Department of Environment and Conservation, Perth.

Sutcliffe K 2003. The conservation status of aquatic insects in south-western Australia. PhD thesis, Murdoch University, Murdoch (unpubl.).

Theischinger G & Endersby I 2009. Identification guide to the Australian Odonata. Department of Environment, Climate Change and Water NSW, Sydney.

Theischinger G & Hawking J H 2006. *The complete field guide to dragonflies of Australia*. CSIRO Publishing, Collingwood.

Thompson J N & Rich K A 2011. Range edges and the molecular divergence of *Greya* moth populations. *Journal of Biogeography* **38**, 551–563.

Timms B V 2009. A study of the saline lakes of the Esperance hinterland, Western Australia, with special reference to the roles of acidity and episodicity. *In*: Oren, A Natfz D L, Palacois P & Wurtsburgh W A (eds) *Saline Lakes Around the World: Unique Systems with Unique Values*, pp. 215–225. Natural Resources and Environmental Issues 15.1. <http://works.bepress.com/wayne_wurtsbaugh/1>

Unmack P J 2001. Biogeography of Australian freshwater fishes. *Journal of Biogeography* **28**, 1053–1089.

Walshe T V, Halse S A, McKenzie N L & Gibson N 2004. Toward identification of an efficient set of conservation recovery catchments for Western Australian wheatbelt biodiversity. *Records of the Western Australian Museum Supplement* **67**, 365–384.

Whitaker D & Christman M 2010. Clustsig: significant cluster analysis package for R, v 1.0.

Williams W D, De Deckker P & Shiel R J 1998. The limnology of Lake Torrens, an episodic salt lake of central Australia, with particular reference to unique events in 1989. *Hydrobiologia* **384**, 101–110.

*Received 1 August 2011; accepted 19 March 2012*

**Appendix 1** Aquatic invertebrates collected from wetlands sampled in the Hutt catchments.

| Taxon | Sample | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3A | 3A | 3B | 3C | 4 | 4 | 5 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 11 | 12A | 12B | 12C | 12D | 13 | 14 | 14 | 15 | 16 |
| | Sep 2007 | Sep 2007 | Feb 2008 | Sep 2007 | Sep 2007 | Feb 2008 | Feb 2008 | Sep 2007 | Feb 2008 | Sep 2007 | Sep 2007 | Sep 2007 | Sep 2007 | Sep 2007 | Sep 2007 | Jul 1999 | Sep 2007 | Sep 2007 | Sep 2007 | Oct 2008 | Jul 1999 | Sep 2007 | Jul 1999 | Sep 2007 | Sep 2007 | Jul 1999 |
| PROTOZOANS | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *Arcella* sp. A | - | - | - | 1 | - | - | - | 1 | - | - | - | - | - | - | 1 | - | 1 | - | - | - | - | - | - | - | - | - |
| *Arcella* sp. B | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Arcella* sp. C | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - |
| *Centropyxis aculeata* | - | 1 | - | - | 1 | 1 | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - |
| *Centropyxis* sp. | - | 1 | - | 1 | - | 1 | - | 1 | - | 1 | - | - | - | - | 1 | - | 1 | - | - | - | - | - | - | - | - | - |
| *Centropyxis* cf. *kahlii* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - |
| *Difflugia* sp. | - | - | - | 1 | - | - | - | 1 | - | - | - | - | - | - | 1 | - | 1 | - | - | - | - | - | - | - | - | - |
| TURBELLARIANS | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Turbellaria | - | - | - | - | - | - | 1 | - | - | 1 | - | - | 1 | - | - | 1 | - | - | - | - | - | - | - | - | 1 | - |
| Nemertines | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Nemertini | - | - | - | - | - | 1 | - | - | - | - | 1 | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - |
| NEMATODES | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Nematoda | - | - | - | - | - | - | 1 | - | - | - | - | 1 | 1 | - | 1 | 1 | - | - | - | - | 1 | 1 | 1 | - | - | 1 |
| ROTIFERS | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Bdelloidea | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - |
| *Brachionus plicatilis* s.l. | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - |
| *Keratella procurva* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - |
| *Colurella adriatica* | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | 1 |
| *Euchlanis deflexa* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - |
| *Lecane bulla* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - |
| *Lecane flexilis* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - |
| *Lecane grandis* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - |
| *Lecane hamata* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - |
| *Lecane ludwigii* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - |
| *Lecane luna* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | 1 |
| *Lecane thalera* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - |
| *Lecane grandis* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - |
| *Tripleuchlanis plicata* | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Cephalodella gibba* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - |

| | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **MOLLUSCS** | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *Plotiopsis* sp. | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - |
| *Ferrissia* sp. | 1 | - | 1 | - | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Glyptophysa* cf. *gibbosa* | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Coxiella striatula* | | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - |
| **OLIGOCHAETES** | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Naididae (ex Tubificidae) | - | - | - | 1 | 1 | 1 | 1 | 1 | - | 1 | - | - | 1 | 1 | - | - | 1 | - | - | - | - | 1 | 1 | - | - | 1 |
| Naidinae (ex Naididae) | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Dero digitata* | 1 | - | - | - | - | 1 | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - |
| *Dero furcata* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 |
| *Allonais ranauana* | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Pristina aequiseta* | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | 1 | - | - | - | - |
| *Pristina jenkinae* | - | - | - | - | 1 | - | - | 1 | - | 1 | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | 1 |
| *Pristina cf. sima* | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - |
| *Chaetogaster diastrophus* | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Limnodrilus hoffmeisteri* | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Potamothrix bavaricus* | 1 | - | - | - | - | 1 | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Ainudrilus nharna* | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - |
| *Insulodrilus lacustris s.l.* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 |
| Enchytraeidae | - | - | - | - | 1 | - | 1 | 1 | - | - | - | 1 | 1 | - | - | 1 | 1 | - | - | - | - | - | 1 | - | - | 1 |
| **WATER MITES** | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *Hydrachna australica* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - |
| *Hydrachna* sp. | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Hydrachna cf. approximata* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - |
| *Austrotrombella sp. nov.* | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Arrenurus* (*Truncaturus*) sp. 25 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - |
| *Arrenurus* sp. HUT008 | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| **BRINE SHRIMP** | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *Artemia* sp. | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | 1 | 1 | - | - | - | - | - |
| **CLADOCERANS** | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *Alona rigidicaudis* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - |
| *Alona* sp. | - | 1 | - | - | - | - | - | - | - | - | - | - | - | 1 | 1 | - | - | - | - | - | - | - | - | 1 | - | - |
| *Alona* cf. *rectangula novaezelandiae* | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Leydigia australis* | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Armatalona macrocopa* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - |
| *Daphnia carinata* | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Simocephalus elizabethae* | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - |
| *Simocephalus* sp. | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - |
| *Macrothrix breviseta* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - |
| *Macrothrix* cf. *breviseta* | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Limnocythere mowbrayensis* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - |
| *Limnocythere porphyretica* | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | 1 | - | - | - | - | - | - | - | - | - | - | - |
| *Ilyocypris australiensis* | - | - | 1 | 1 | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - |

| Taxon | Sample | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3A | 3A | 3B | 3C | 4 | 4 | 5 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 11 | 12A | 12B | 12C | 12D | 13 | 14 | 14 | 15 | 16 |
| | Sep 2007 | Sep 2007 | Feb 2008 | Sep 2007 | Sep 2007 | Feb 2008 | Feb 2008 | Sep 2007 | Feb 2008 | Sep 2007 | Sep 2007 | Sep 2007 | Sep 2007 | Sep 2007 | Sep 2007 | Jul 1999 | Sep 2007 | Sep 2007 | Sep 2007 | Oct 2008 | Jul 1999 | Sep 2007 | Jul 1999 | Sep 2007 | Sep 2007 | Jul 1999 |
| *Candonopsis tenuis* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 |
| *Alboa worooa* | 1 | - | 1 | 1 | 1 | - | - | - | - | 1 | - | 1 | - | 1 | - | - | - | - | - | - | - | - | 1 | 1 | 1 | 1 |
| *Australocypris insularis* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - |
| *Bennelongia* sp. 4 | - | - | - | - | - | - | - | - | - | - | - | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Candonocypris novaezelandiae* | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | - | 1 | 1 | 1 | 1 | - | - | - | - | - | - | 1 | - | 1 |
| *Cypretta baylyi* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - |
| *Cypretta* sp. | - | - | - | 1 | 1 | - | - | - | - | 1 | - | 1 | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - |
| *Diacypris spinosa* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | 1 | - | - | - | - | - | 1 | - |
| *Heterocypris* sp. | - | - | - | - | - | - | - | - | - | - | - | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Mytilocypris mytiloides* | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | 1 | 1 | - | - | 1 | - | - | 1 | - |
| *Ilyodromus* sp. | - | - | - | - | 1 | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 |
| *Sarscypridopsis aculeata* | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | - | 1 | - | 1 | 1 | 1 | 1 | 1 | 1 | - | - | - | - | - | 1 | 1 | - | 1 |
| *Kennethia cristata* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | 1 | 1 | 1 | - |
| *Paradoxostoma* sp. | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | 1 | - | - | - | - | - | - |
| **COPEPODS** | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *Calamoecia clitellata* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | | 1 | | - | - | - | - | - | - |
| *Calamoecia* sp. | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - |
| *Microcyclops varicans* | - | - | - | 1 | - | - | - | - | - | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Metacyclops* sp. 462 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | 1 | - | - | - | - | - | - | - | - | - |
| *Metacyclops* sp. 434 | - | - | - | - | - | - | - | - | - | - | - | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Australocyclops australis* | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - |
| *Halicyclops ambiguus* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - |
| *Macrocyclops albidus* | 1 | 1 | - | - | - | 1 | 1 | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | 1 |
| *Mesocyclops brooksi* | - | - | 1 | 1 | 1 | 1 | 1 | - | 1 | - | - | - | - | 1 | 1 | - | 1 | - | 1 | - | - | 1 | 1 | 1 | 1 | - |
| *Mesocyclops* sp. | - | - | - | - | - | - | - | 1 | - | 1 | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - |
| *Eucyclops australiensis* | 1 | 1 | - | - | - | 1 | 1 | 1 | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | 1 | - | - |
| *Paracyclops chiltoni* | 1 | 1 | 1 | - | 1 | 1 | - | - | - | - | 1 | - | - | 1 | 1 | - | 1 | - | - | - | - | - | - | - | - | 1 |
| *Paracyclops* sp. | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - |
| *Paracyclops* sp 1 ( cf. *timmsi*) | 1 | 1 | - | - | - | - | 1 | - | - | - | 1 | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | 1 |
| *Onychocamptus bengalensis* | - | - | 1 | - | - | - | 1 | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - |
| *Robertsonia* sp. | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - |
| *Nitocra? reducta* (sp. 5) | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - |
| *Nitocra* sp. 3 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - |
| *Nitocra* sp. 5 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | 1 | - | - | 1 | - |
| Lourinidae | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - |
| Harpacticoida sp. 2 | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |

| | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **AMPHIPODS** | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *Austrochiltonia subtenuis* | 1 | 1 | 1 | - | 1 | 1 | - | 1 | 1 | 1 | 1 | - | - | - | - | 1 | 1 | 1 | 1 | 1 | - | 1 | 1 | 1 | 1 | 1 |
| **ISOPODS** | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Philosciidae | - | - | - | - | - | - | - | - | - | - | - | - | — | - | - | - | - | - | - | - | 1 | - | - | - | - | - |
| **DECAPODS** | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *Cherax destructor* | - | - | - | - | - | 1 | - | - | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Cherax caini* | - | 1 | - | - | - | 1 | 1 | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 |
| **COLEOPTERANS** | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *Haliplus fuscatus* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - |
| *Haliplus gibbus* | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Neohydrocoptus subfasciatus* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - |
| *Hyphydrus elegans* | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | 1 | 1 | - | - |
| *Hyphydrus* sp. | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - |
| *Hydroglyphus leai* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | 1 | - | - | - | - |
| *Limbodessus inornatus* | 1 | - | - | - | 1 | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Allodessus bistrigatus* | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Paroster* sp. | - | - | - | - | 1 | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | 1 |
| *Sternopriscus sp.* | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - |
| *Necterosoma penicillatus* | - | - | 1 | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | 1 | - | - |
| *Necterosoma darwini* | - | - | - | - | - | - | 1 | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Necterosoma* sp. | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | 1 | - |
| *Megaporus ruficeps* | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Megaporus* sp. | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | 1 | - |
| *Platynectes aenescens* | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Platynectes decempunctatus* var *decempunctatus* | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Platynectes* sp. | - | - | 1 | - | - | - | - | 1 | - | 1 | - | - | 1 | - | 1 | 1 | - | - | - | - | - | - | - | - | - | 1 |
| *Rhantus suturalis* | - | - | 1 | 1 | 1 | - | 1 | - | 1 | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Rhantus* sp. | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Eretes australis* | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Eretes* sp. | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Onychohydrus* sp. | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | 1 | - | - |
| Dytiscidae | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - |
| Bidessini | - | - | - | - | 1 | - | - | - | - | - | - | 1 | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - |
| *Macrogyrus angustatus* | - | 1 | 1 | 1 | 1 | 1 | 1 | - | 1 | 1 | 1 | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - |
| *Macrogyrus* sp. | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Aulonogyrus strigosus* | - | 1 | - | 1 | - | 1 | 1 | 1 | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Gyrinidae | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Berosus approximans* | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | 1 | - | - | - |
| *Berosus discolor* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - |
| *Berosus* sp. | - | - | 1 | 1 | - | - | - | - | 1 | - | - | - | - | - | - | 1 | - | - | - | - | - | 1 | - | - | - | - |
| *Helochares tenuistriatus* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - |
| *Helochares tatei* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - |
| *Helochares sp.* | - | - | 1 | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Limnoxenus zelandicus* | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |

| Taxon | Sample | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 Sep 2007 | 2 Sep 2007 | 3A Feb 2008 | 3A Sep 2007 | 3B Sep 2007 | 3C Feb 2008 | 4 Feb 2008 | 4 Sep 2007 | 5 Feb 2008 | 5 Sep 2007 | 6 Sep 2007 | 7 Sep 2007 | 8 Sep 2007 | 9 Sep 2007 | 10 Sep 2007 | 11 Jul 1999 | 11 Sep 2007 | 12A Sep 2007 | 12B Sep 2007 | 12C Oct 2008 | 12D Jul 1999 | 13 Sep 2007 | 14 Jul 1999 | 14 Sep 2007 | 15 Sep 2007 | 16 Jul 1999 |
| *Limnoxenus* sp. | - | - | - | 1 | 1 | - | - | - | - | 1 | 1 | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Paracymus pygmaeus* | - | - | - | - | 1 | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Paracymus* sp. | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - |
| Hydrophilidae | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | 1 | 1 | - | 1 | - | - | - | - | - |
| *Ochthebius* sp. | - | - | 1 | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Staphylinidae | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - |
| Scirtidae | 1 | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | 1 | 1 | - | - | - | - | - | 1 | - | 1 | - |
| Limnichidae | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - |
| Brentidae | - | - | - | - | - | 1 | - | - | - | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Curculionidae | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | | | | | | | | DIPTERANS | | | | | | | | | | | | | | | | |
| Diptera | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - |
| Tipulidae type A | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Tipulidae type C | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Tipulidae type E | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Tipulidae type F | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - |
| Tipulidae type H | 1 | - | - | 1 | - | - | - | - | 1 | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Anopheles annulipes* s.l. | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | 1 | - |
| *Anopheles atratipes* | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Anopheles* sp. | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Aedes alboannulotus* | - | - | - | - | 1 | - | - | - | - | - | - | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Aedes camptorhynchus* | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Aedes cf. camptorhynchus* | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Culiseta atra* | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Culex globocoxitus* | - | - | - | - | - | - | - | - | - | - | - | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Culex* (*Culex*) *australicus* | - | - | - | 1 | 1 | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 |
| *Culex* sp. 3 | - | - | - | - | 1 | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Bezzia* sp. | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - |
| *Bezzia* sp. 2 | - | 1 | 1 | - | - | - | 1 | 1 | - | 1 | 1 | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - |
| *Bezzia* sp. 1 | 1 | - | - | 1 | - | 1 | 1 | 1 | 1 | 1 | 1 | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - |
| *Culicoides* sp. | 1 | 1 | 1 | 1 | 1 | 1 | - | 1 | - | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | - | 1 | - | 1 | - | - | - | - | - |
| *Monohelea* sp. | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 |
| *Monohelea* sp. 1 | - | - | - | 1 | - | 1 | 1 | - | 1 | 1 | 1 | - | - | - | 1 | - | 1 | - | - | - | - | - | - | - | - | - |
| *Monohelea* sp. 2 | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Monohelea* sp. 4 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - |
| *Nilobezzia* sp. | - | - | 1 | - | - | 1 | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Atrichopogon* sp. 2 | - | - | 1 | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Forcypomyia* sp. | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - |
| *Forcypomyia* sp. 2 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |

| | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Forcypomyia* sp. 6 | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Forcypomyia* sp. 7 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Forcypomyia* sp. 8 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Forcypomyia* sp. 9 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Dasyhelea* sp. | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - |
| Ceratopogonidae | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - |
| Dasyheleinae | - | - | - | - | 1 | 1 | 1 | 1 | 1 | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Tabanidae | 1 | - | - | - | - | - | - | - | 1 | 1 | - | - | - | - | - | 1 | - | - | - | - | - | - | 1 | - | - | - |
| Stratiomyidae | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | 1 | - | - | - | 1 | 1 | - | 1 | - | - | - |
| Empididae | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Dolichopodidae | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - |
| Dolichopodidae sp. A | - | - | - | - | 1 | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Sciomyzidae | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Ephydridae | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - |
| Ephydridae sp. 2 | - | - | - | - | 1 | - | - | - | - | - | - | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - | 1 | - |
| Ephydridae sp. 3 | - | - | - | - | 1 | - | - | - | - | - | - | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Ephydridae sp. 4 | - | - | - | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Ephydridae sp. 6 | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | 1 | 1 | - | 1 | - | - | - |
| Ephydridae sp. 12 | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Ephydridae sp. 13 | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Muscidae | - | - | - | - | - | - | - | - | 1 | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Muscidae sp. A | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | 1 | - | - | - | - | - |
| Diptera sp. E | 1 | 1 | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Procladius paludicola* | 1 | - | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | - | - | - | - | 1 | 1 | 1 | - | - | 1 | - | - | - | 1 | - |
| -*Procladius villosimanus* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | 1 | 1 | - | 1 |
| *Alotanypus dalyupensis* | - | 1 | - | - | 1 | 1 | - | - | - | - | 1 | - | - | 1 | 1 | - | - | - | - | - | - | - | 1 | - | - | - |
| *Ablabesmyia notabilis* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 |
| *Paramerina levidensis* | - | 1 | - | 1 | 1 | - | - | 1 | 1 | 1 | 1 | 1 | - | 1 | 1 | 1 | 1 | - | - | - | - | - | 1 | 1 | - | - |
| *Larsia albiceps* | - | - | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Parakiefferiella* sp. A | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | 1 | - | - | - | - | - | - | - | - | - | 1 |
| *Nanocladius* sp. 1 (VCD7) | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Corynoneura* sp. | 1 | - | - | - | 1 | - | - | - | - | - | - | 1 | - | - | 1 | - | 1 | - | - | - | - | - | - | 1 | - | - |
| *Corynoneura* sp. (V49) | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | 1 | - | - | - |
| *Thienemanniella* sp. (V19) | - | 1 | - | 1 | - | - | - | 1 | - | 1 | 1 | - | - | 1 | 1 | - | 1 | - | - | - | - | - | - | - | - | 1 |
| *Paralimnophyes pullulus* | 1 | 1 | - | 1 | 1 | - | - | - | - | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | - | - | - | - | 1 | - | - | - | - |
| *Cricotopus albitarsus* | 1 | 1 | - | 1 | - | 1 | - | 1 | - | - | - | - | - | - | 1 | 1 | - | - | - | - | - | - | - | - | - | - |
| *Paraimnophyes* sp. A | - | 1 | - | - | - | - | - | 1 | - | - | 1 | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | 1 |
| Orthocladiinae | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - |
| Orthocladiinae sp. A (?VSC11) | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Orthocladiinae sp. I | 1 | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | 1 | - | - | - | - | - | - | - | - | - |
| Orthocladiinae S03 sp. A | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 |
| Orthocladiinae sp. G | - | - | 1 | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | 1 | 1 | - | - | - | - | - |
| *Cladotanytarsus* sp. A | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Tanytarsus barbitarsis* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | 1 | 1 | 1 | - | - | - | - | - |
| *Tanytarsus palmatus* | 1 | 1 | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | 1 |
| *Tanytarsus* sp. C (*bispinosus*) | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Tanytarsus* sp. D | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - |
| *Tanytarsus* sp. G | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - |
| *Tanytarsus* sp. H | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |

| Taxon | Sample | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3A | 3A | 3B | 3C | 4 | 4 | 5 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 11 | 12A | 12B | 12C | 12D | 13 | 14 | 14 | 15 | 16 |
| | Sep 2007 | Sep 2007 | Feb 2008 | Sep 2007 | Sep 2007 | Feb 2008 | Feb 2008 | Sep 2007 | Feb 2008 | Sep 2007 | Sep 2007 | Sep 2007 | Sep 2007 | Sep 2007 | Sep 2007 | Jul 1999 | Sep 2007 | Sep 2007 | Sep 2007 | Oct 2008 | Jul 1999 | Sep 2007 | Jul 1999 | Sep 2007 | Sep 2007 | Jul 1999 |
| *Tanytarsus* nr *bispinosus* | 1 | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - |
| *Tanytarsus fuscithorax/ semibarbitarsus* | - | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | - | - | - | - | - | 1 | 1 | 1 | - | - |
| *Rheotanytarsus juliae* | - | - | - | 1 | - | 1 | - | 1 | 1 | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Rheotanytarsus* sp. | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 |
| *Kiefferulus intertinctus* | - | - | 1 | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | 1 | 1 | - | - | - |
| *Polypedilum leei* | - | - | - | - | - | - | - | - | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Polypedilum nubifer* | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | 1 | 1 | - | - | - | - | - | 1 | - | 1 | - | - |
| *Polypedilum* cf. *convexum* | - | 1 | 1 | - | - | - | - | - | - | - | - | - | - | 1 | - | 1 | 1 | - | - | - | - | - | - | - | - | - |
| *Paraborniella tonnoiri* | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Cryptochironomus griseidorsum* | - | 1 | 1 | 1 | - | - | - | 1 | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Cladopelma curtivalva* | - | - | 1 | - | - | 1 | 1 | 1 | - | 1 | 1 | - | - | - | 1 | - | - | - | - | - | - | - | - | - | 1 | - |
| EPHEMEROPTERANS | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Baetidae | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Cloeon* sp. | - | - | -1 | 1 | 1 | 1 | - | - | 1 | 1 | - | - | - | 1 | 1 | 1 | - | - | - | - | - | - | 1 | 1 | - | 1 |
| *Tasmanocoenis tillyardi* | - | 1 | - | 1 | - | 1 | 1 | 1 | 1 | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 |
| HEMIPTERANS | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *Hydrometra strigosa* | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Microvelia (Pacificovelia) oceanica* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - |
| *Microvelia (Austromicrovelia) peramoena* | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - |
| *Microvelia* sp. | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - |
| Veliidae | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | 1 | - | - | - | - | 1 | - | - | - | - |
| *Laccotrephes tristis* | 1 | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Agraptocorixa eurynome* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | 1 | 1 | - | - |
| *Agraptocorixa* sp. | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | 1 | - |
| *Micronecta robusta* | - | - | 1 | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | 1 | - |
| *Micronecta* sp. | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Corixidae | - | - | 1 | - | 1 | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | 1 | - | 1 | - | - |
| *Anisops thienemanni* | - | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | 1 | - | 1 | - |
| *Anisops elstoni* | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | 1 | 1 | - | - |
| *Anisops nasuta* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - |
| *Anisops stali* | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Anisops* sp. | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | 1 | - | - | - | - | - | - | - | - | - | - | 1 |
| Notonectidae | - | - | - | - | 1 | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | 1 | - | 1 | - | - |
| *Paraplea* sp. | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - |
| *Paraplea* n. sp. (ANIC 6) | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - |

| | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **LEPIDOPTERANS** | | | | | | | | | | | | | | | | | | | | | | | | | |
| Lepidoptera sp. | 1 | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | 1 | - | 1 | - | - | - | - | - | - | - |
| Pyralidae sp. | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Pyralidae cf. sp. 39/40 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - |
| Lepidoptera (non-pyralid) sp. 3 | 1 | - | - | 1 | 1 | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Lepidoptera (non-pyralid) Pilbara sp. 3 | - | - | - | - | - | - | - | - | - | 1 | - | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| **ODONATES** | | | | | | | | | | | | | | | | | | | | | | | | | |
| Epiproctophora (=Anisoptera) sp. | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Austroagrion cyane* | - | - | - | - | - | - | - | - | - | 1 | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | 1 |
| *Ischnura aurora aurora* | 1 | - | - | - | 1 | - | - | - | 1 | - | - | - | - | 1 | - | 1 | - | - | - | - | - | - | 1 | - | - | - |
| *Ischnura heterosticta heterosticta* | 1 | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | 1 | - | - |
| *Austrolestes psyche* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - |
| *Archiargiolestes pusillus* | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Adversaeschna brevistyla* | - | 1 | - | - | - | 1 | - | - | 1 | - | - | - | - | 1 | - | 1 | 1 | - | - | - | - | - | - | - | - | - |
| *Hemianax papuensis* | - | - | - | 1 | 1 | - | - | - | - | 1 | - | - | - | - | 1 | 1 | - | - | - | - | - | 1 | 1 | 1 | 1 | - |
| Aeshnidae | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - |
| Corduliidae | - | - | - | - | - | - | - | - | - | - | 1 | 1 | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - |
| *Diplacodes bipunctata* | — | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - |
| *Nannophya dalei* | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - |
| *Orthetrum caledonicum* | - | 1 | 1 | - | - | 1 | 1 | - | 1 | - | 1 | - | - | - | - | 1 | - | - | - | - | - | - | 1 | 1 | - | - |
| *Orthetrum pruinosum migratum* | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Archaeosynthemis occidentalis* | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - |
| *Hemicordulia australiae* | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Hemicordulia tau* | - | 1 | 1 | 1 | 1 | - | 1 | - | 1 | 1 | 1 | - | - | 1 | 1 | 1 | - | - | - | - | - | - | - | 1 | - | 1 |
| **TRICHOPTERANS** | | | | | | | | | | | | | | | | | | | | | | | | | |
| *Trichoptera* sp. | - | - | - | - | - | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Acritoptila globosa* | - | - | - | 1 | - | 1 | 1 | 1 | - | 1 | 1 | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - |
| *Hellyethira litua* | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Oxyethira* sp. | - | - | 1 | - | - | - | - | 1 | - | 1 | 1 | - | - | - | - | 1 | 1 | - | - | - | - | - | - | - | - | - |
| *Cheumatopsyche* sp. AV2 | - | - | - | 1 | - | - | 1 | 1 | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Hydropsychidae | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - |
| *Ecnomus pansus* | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Ecnomidae | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Oecetis* sp. | - | - | 1 | 1 | - | - | - | - | - | 1 | 1 | - | - | - | - | - | - | - | - | - | - | 1 | 1 | - | - | - |
| *Triplectides australis* | - | - | - | 1 | - | 1 | | - | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | 1 | 1 | - | - |

Journal of the Royal Society of Western Australia, 95: 53–62, 2012

# Anthropogenic land subsidence in the Perth Basin: challenges for its retrospective geodetic detection*

**W E FEATHERSTONE[1†], M S FILMER[1], N T PENNA[2], L M MORGAN[3] AND A SCHENK[4]**

[1] *Western Australian Centre for Geodesy & The Institute for Geoscience Research, Curtin University of Technology, GPO Box U1987, Perth WA 6845, Australia*

[2] *School of Civil Engineering and Geosciences, Newcastle University, Newcastle upon Tyne, NE1 7RU, United Kingdom*

[3] *Landgate, PO Box 2222, Midland WA 6936, Australia*

[4] *Geodetic Institute, Karlsruhe Institute of Technology, Englerstrasse 7, 76131 Karlsruhe, Germany*

[†] *Corresponding author* ✉ *W.Featherstone@curtin.edu.au*

******This paper is dedicated to the memory of Kevin Pownall*

Recent-past subsidence of parts of the Perth Basin has most probably been caused by increased groundwater extraction for domestic and agricultural use. However, no dedicated geodetic monitoring programs were established when the increased extraction began in around 2000, thus setting a challenge to retrospectively quantify and map the subsidence. Differential levelling is likely to be less effective as only a few repeat traverses cover the areas thought to be subsiding. Repeat gravimetry is totally ineffective because of microseismic vibrations propagating through the Perth Basin. Repeat episodic GPS (Global Positioning System) is also likely to be less effective because of the few station occupations over several days or weeks and the inherent weakness of GPS for height determination. However, from a continuously operating GPS receiver at Gnangara and nearby artesian monitoring boreholes, we show that the rate of land subsidence has slowed from about -6 mm/yr to about -2 mm/yr since the reduction of groundwater extraction from the Yarragadee Aquifer in around 2005. A promising technique is InSAR (interferometric synthetic aperture radar) because it can map large areas, but the lack of historical radar imagery over the period of increased subsidence is a hindrance.

**KEYWORDS: geodesy, GPS, gravity, InSAR, land subsidence, levelling, Perth Basin.**

## INTRODUCTION

A broad definition of modern geodesy is that it comprises the determination of the size, shape and external gravity field of the Earth, including spatiotemporal variations in these quantities (Featherstone 2008). One example of the latter is the quantification, mapping and monitoring of land subsidence, usually followed by interpretation and explanation of the physical causes, if possible, and any consequences. However, the proper geodetic quantification of land subsidence requires time series of observations, the longer the better (Coates *et al.* 1985), but these may not always be available in an area that was not expected to be subsiding. This will be exemplified in this discussion for the Perth Basin.

The Perth Basin largely comprises ~15 km of sedimentary rocks that contain several confined and unconfined freshwater aquifers, and which abuts the Yilgarn Craton to the east at the near-vertical Darling Fault. The Darling Fault is currently aseismic (Jakica *et al.* 2011), yet vertical ground motion of around -5 mm/yr [by geodetic convention, a negative sign indicates subsidence] has been detected by a continuously operating Global Positioning System (GPS) receiver at Gnangara (Bouin & Wöppelmann 2010), which is located on the Perth Basin. Bouin & Wöppelmann (2010 p. 204) could give no explanation for the subsidence, stating 'this may reflect a local subsidence of the GPS station, as this part of Australia is not susceptible to tectonic deformation'. This is true, as local knowledge (see later) suggests it is likely to be associated with groundwater extraction to satisfy domestic and agricultural demand.

In 2007–2008, the Western Australian news media reported an alarming amount of subsidence in the Perth Basin, claiming up to -50 mm/yr in some metropolitan suburbs, and attributed it largely to groundwater extraction. This was based on a press release originating from the University of New South Wales and promulgated by the Cooperative Research Centre for Spatial Information. It appears that this was an overestimate by one order of magnitude based on the work of Dawson (2008) and the work presented herein. The press release was based on a conference paper (Ng & Ge 2007) that had not used independent observations to cross-validate their interferometric synthetic aperture radar (InSAR) results (Zerbini *et al.* 2007), or local knowledge such as fissures and infrastructure cracking that would be likely at this rate of subsidence. The news media did not seek independent corroboration: this is akin to the exemplary case of cold nuclear fusion (Ackermann 2006), where a press release was made before subjecting the findings to peer-review.

Proper quantification, mapping and monitoring of recent-past subsidence in the Perth Basin also have implications for sea-level change measurements, because the Fremantle and Hillarys tide-gauges are located on it. Fremantle provides a long-term record (since 1897) that has been given substantial weight in global sea-level projections (Church & White 2006), notably because it is one of relatively few long-term records in the Southern Hemisphere. However, tide-gauges only measure sea-level change relative to the land, so if the land is subsiding, the relative sea-level change will be contaminated (Belperio 1993; Aubrey & Emery 1986), as will be any future projections (Mörner 2004). In short, coastal land subsidence causes sea-level rise measurements to be exacerbated, but it also makes low-lying coastal areas more vulnerable to seawater inundations (Brunn 1988).

Due to increased domestic and agricultural demand from the increasing population of the city of Perth and its environs, the Western Australian Department of Water significantly increased extraction of groundwater from the confined Yarragadee Aquifer around the year 2000. Figure 1 exemplifies this for the AM27 artesian monitoring borehole in the north Perth metropolitan region (WA Department of Water code 61615063). There has also been groundwater extraction from the confined Leederville Aquifer, but the drawdown from the Yarragadee Aquifer is more substantial over the recent past (Figure 1).

Simplistically, the extraction of groundwater from a confined aquifer allows the weight of the overlying sediments to compress the sediments that previously hosted the groundwater, resulting in land subsidence. The physics of the processes is beyond the scope of this paper, but the correlation between groundwater extraction and land subsidence is well documented (Chi & Reilinger 1984; Bawden *et al.* 2001), and will be demonstrated later in this paper.

More specifically, we will review the geodetic quantification and mapping of recent-past subsidence in the context of the Perth Basin, and somewhat uniquely in that no dedicated geodetic monitoring programs had been established before, during or after the groundwater extraction was increased. The groundwater extraction from the Yarragadee Aquifer reduced significantly around 2005 (Figure 1), so there is the additional consideration if there is any time delay of the subsidence or whether it has now slowed, stopped or if there is rebound due to replenishment of the aquifer. Again, this is problematic because of the need for historical time series of geodetic data.

## LIMITATIONS ON GEODETIC METHODS IN THE PERTH BASIN

The principal problem with trying to determine land subsidence retrospectively in the Perth Basin is the lack of repeat geodetic observations, and preferably continuous or regularly sampled time series so that trends and changes in trends can be determined more reliably (Coates *et al.* 1985). The geodetic techniques comprise both terrestrial and space-borne observations. Terrestrial techniques include repeat differential levelling and repeat gravimetry. Space-borne techniques include InSAR and repeat episodic or continuous GPS observations.

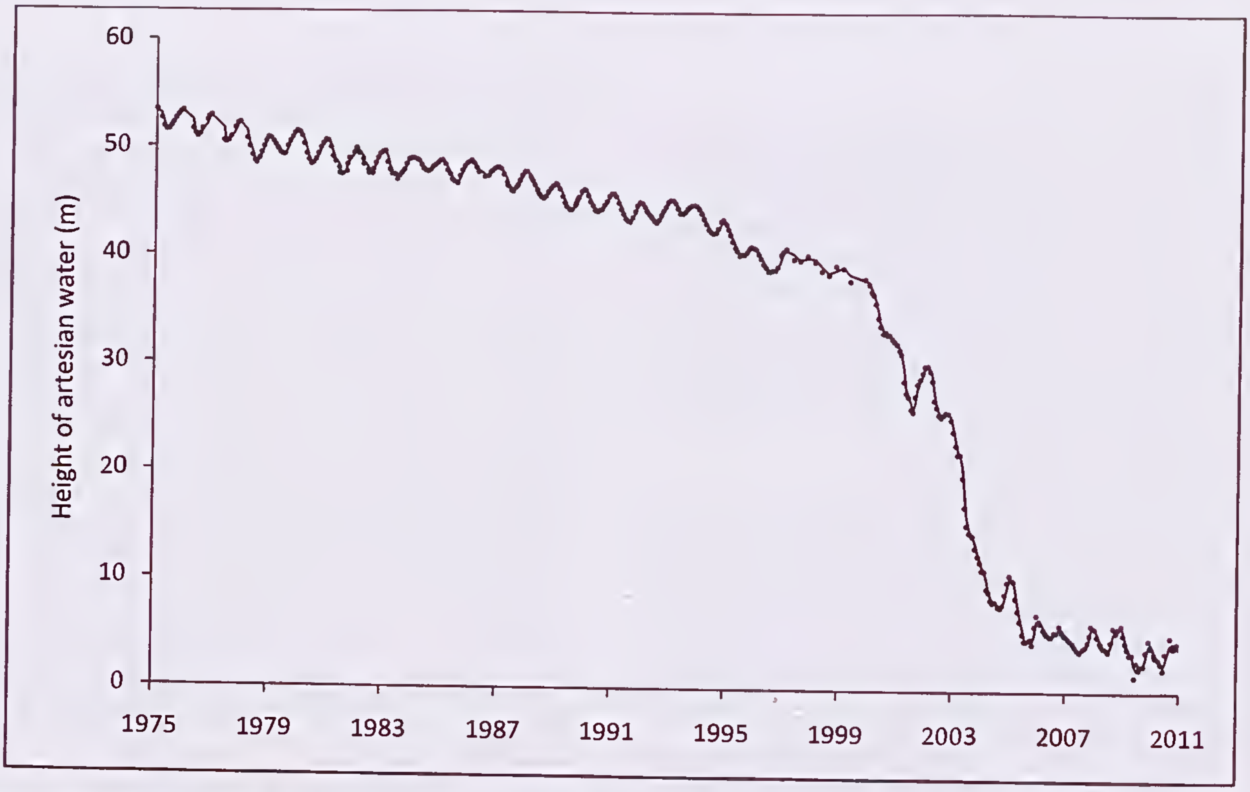


**Figure 1.** Change in height (in metres) relative to an arbitrary datum of the water level in the Yarragadee Aquifer, showing that it dropped by ~32m between ~2000 and ~2005 at the AM27 borehole. The oscillations are due to seasonal recharge and discharge. Data courtesy of the WA Department of Water (http://www.water.wa.gov.au/Tools/Monitoring+and+data/default.aspx).

All these techniques should be used relative to a vertically stable frame of reference. Fortunately in this case, the Yilgarn Craton to the east of the Darling Fault can provide such a reference for the terrestrial observations of repeat levelling and repeat gravimetry, where no vertical displacement is assumed. However, as will be discussed in the sequel, very few such observations have been collected on this craton. The space-based observations of InSAR and repeat or continuously operating GPS are tied to a global reference frame as implied via the satellite orbits. Nevertheless, their vertical stability could be 'calibrated' through observations on this craton, but yet again few such observations are available.

### Repeat levelling

Differential levelling measures the height difference between ground monuments (benchmarks) using a levelling instrument located between two graduated and calibrated staves. It is the most precise means of determining heights and height differences (Vaníček *et al.* 1980). Details of the field and data reduction methods involved are given in any land surveying textbook and national standards are set for tolerances (ICSM 2007). Levelling has been used by Landgate, the Western Australian land information agency, and its predecessor organisations (collectively referred to as Landgate), to provide reliable heights to its stakeholders. However, this has not been specifically for monitoring subsidence in the Perth Basin.

The Australian Height Datum (AHD) forms the vertical frame of reference for heights across the continent (Roelse *et al.* 1975), and Landgate is responsible for maintaining the provision of AHD heights to its stakeholders through a network of physical benchmarks in Western Australia. Much of Landgate's levelling operations since the establishment of the AHD in 1971 have focussed on densifying the coverage of benchmarks and maintenance by replacing disturbed and destroyed benchmarks or correcting erroneous levelling traverses when identified. Virtually no past operational focus has been on repeat levelling for the purpose of detecting subsidence or uplift. As such, there are very few repeat levelling observations that can be used to retrospectively detect subsidence in the Perth Basin (Figure 2). One repeat levelling survey was conducted in 1986 following the 1968 Meckering earthquake (Wellman & Tracey 1987). However, this repeat levelling did not cover very much of the Perth Basin, with only four traverses south of the Swan River.

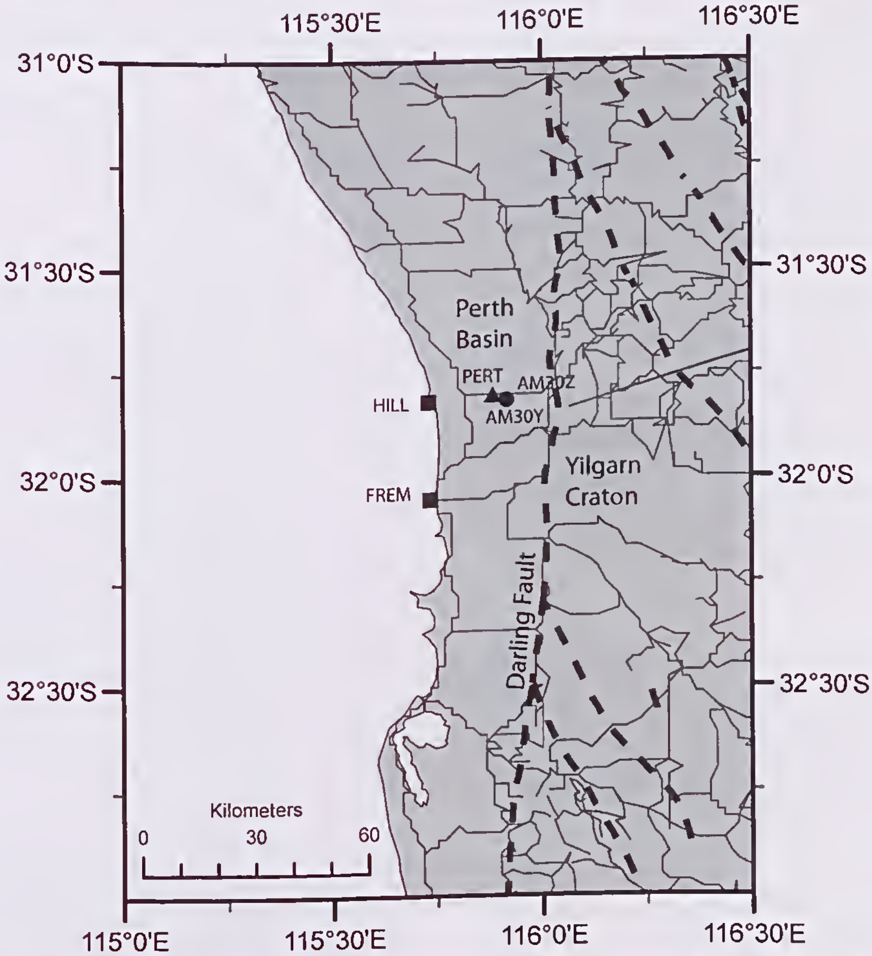


**Figure 2.** Levelling traverses (thin black lines) around Perth, location of tide gauges (black squares) at Hillarys (HILL) and Fremantle (FREM), location of the AM30Y and AM30Z artesian monitoring bores (black circle), and location of the PERT continuous GPS station at Ganagara (black triangle). The thick dashed black lines denote major faults, notably the north–south Darling Fault dividing the Perth Basin to the west from the Yilgarn Craton to the east. Data courtesy of Geoscience Australia and the Geological Survey of Western Australia.

When maintaining the provision of heights to users, it is convenient and cost-effective to conduct levelling from the nearest benchmarks, using as many as practically possible so as to ensure observational redundancy. For instance, if a benchmark is disturbed or destroyed, the replacement benchmark's new height is normally determined with respect to several nearby benchmarks, which may be only a few hundred metres apart in some metropolitan regions. Therefore, if that region is subsiding at the same rate, then it will be 'invisible' to differential levelling. This is where connection to a stable frame or point(s) of reference is needed. Thus, if repeat levelling traverses were begun or ended on the Yilgarn Craton, the subsidence in the Perth Basin could be detected. The principal problem is that no such observations had been collected over the period of increased groundwater extraction (~2000–2005; Figure 1).

Taking the ICSM (2007)-recommended allowable misclosure for class L2A levelling (the highest quality in Australia, but also the most labour intensive) over the ~50 km-wide Perth Basin (Figure 2) will permit a height difference of 14 mm to be detected at ~50 km west of the Darling Fault. The same value would apply to a repeated class L2A levelling traverse. If we assume that GPS-derived subsidence of around -5 mm/yr has occurred in the Perth Basin (described later), then independent repeat class L2A levelling might only be able to start to detect subsidence if re-observed after four years. If more confidence is required in any observable vertical velocity, then the re-observation time will increase accordingly.

Importantly, however, a misclosure tolerance is not the same as a standard error (Filmer & Featherstone 2009; Kearsley *et al.* 1993; Morgan 1992), and as most levelling surveys are well within the allowable misclosure, the above-stated frequency required for detection could possibly be reduced. Also, systematic levelling errors such as atmospheric refraction or staff/instrument miscalibration (Angus-Leppan 1979; Craymer & Vaníček 1986) are not accounted for in the above estimate. Another problem in terms of a future monitoring program using precision levelling is its labour-intensive nature. However, repeat levelling has already proven useful in the detection of vertical deformation elsewhere (Chen *et al.* 2011). There is some scope for detecting subsidence in the Perth Basin if levelling is repeated now or sometime in the future. However, the costs are likely to be prohibitive.

### Repeat gravimetry

Since gravitational acceleration decays as an inverse square function of the distance from the attracting masses (i.e. Newton's law of gravitation), repeat gravimetry or gravity measurements can be used to infer changes in height (Biró 1983). Taking the linear decay of model gravity in free air of 0.3086 mGal/m (Moritz 1980), a change in gravity of 0.01 mGal infers a change in height of ~31 mm. However, using gravimetry to infer height changes is a non-unique problem, because changes in the mass distribution in the Earth (e.g. due to the extraction of large amounts of groundwater) also cause gravity to change. As such, repeat gravimetry is a less reliable geodetic monitoring technique, but it has been used to corroborate subsidence from other geodetic techniques (Zerbini *et al.* 2007; Hwang *et al.* 2010).

Gravity can be measured by using absolute or relative techniques (Torge 1989).

Absolute gravimetry uses the fundamental dimensions of length and time, provided by laser, to measure the rise and fall of a proof mass in vacuum. Absolute gravity meters are very expensive (~$800 000) and observations need to be conducted over several days under quite rigid operating conditions. As such, they are not realistic for quantification and mapping of subsidence over the Perth Basin. Moreover, there are very few historical absolute gravity measurements on the Perth Basin, and microseismic noise (described below) renders this technique unsuitable.

Relative gravimetry uses a spring-mounted proof mass to sense changes in gravity, akin to a very sensitive set of weighing scales. Relative gravimeters are prone to instrumental drift, so a base station must be reoccupied before and after (and ideally during) the field survey to monitor, model and account for the drift. Relative gravimeters are much cheaper than absolute ones (~$100 000). Depending on distance between observation stations, a gravity survey crew can collect many (tens to hundreds) stations in a day.

The principal restriction to using repeat relative gravimetry to estimate subsidence in the Perth Basin is the presence of microseismic noise caused by vibrations from ocean-wave action propagated through the sediments of the Perth Basin, as well as from wind action on vegetation. A feasibility survey was conducted in August 2011 to reoccupy some gravity stations observed in November 2000 (Kirby 2003). Assuming a linear -5 mm/yr rate of subsidence, the total change in height should be around -55 mm over this time period, equating to a change in gravity of around 0.017 mGal. In ideal operating conditions, a modern relative gravimeter (we used a Scintrex CG5) can observe gravity to 0.01 mGal, equivalent to ~31 mm. However, the microseismic noise in the Perth Basin in August 2011 was around ±0.2 mGal, whereas it was roughly half this for measurements made in a forested area of the Yilgarn Craton (on quite a windy day).

This amount of noise makes any gravity-based detection of subsidence in the Perth Basin totally inconclusive. A noise level of ±0.2 mGal equates to a height uncertainty of ~±648 mm, just over an order of magnitude larger than the postulated -55 mm subsidence. In addition, the ways in which regional gravity surveys are conducted mean that this uncertainty is compounded by the need to monitor instrumental drift. From the ±0.1 mGal noise at a base station on the Yilgarn Craton during the August 2011 feasibility survey, this could add as much as a further ~±309 mm height uncertainty.

Another problem in the Perth region is that some of the gravity base-station monuments that allow connection to the November 2000 survey have been destroyed. These are Mt Gunjin (Geoscience Australia code 7391.0217) and Perth domestic airport (Geoscience Australia code 9191.0117). The gravimeter calibration line between Mundaring Weir and Mt Gunjin is now defunct because the ground mark at Mt Gunjin has been removed, presumably due to vandalism. The base station at Perth airport seems to have suffered from 'aesthetic vandalism' during refurbishment of the domestic terminal, where a faint mark remains after field inspection based on the original access details. We have reported both destructions to Geoscience Australia.

The above factors compound to render repeat gravimetry a technique largely unsuitable for retrospective or future determination of the subsidence of the Perth Basin.

### Repeat GPS

GPS provides the ellipsoidal height of a ground monument relative to a geometrical figure of the Earth. Although ellipsoidal heights are incompatible with those derived from levelling, repeat determinations of ellipsoidal height can be used to determine the geometrical rate of subsidence. Details of the field and data reduction methods involved are given in any GPS surveying textbook. However, GPS is inherently poorer for the determination of heights than horizontal locations, because of the geometry of the satellites above the receiver and the adverse impacts of atmospheric refraction (Rothacher 2002). A long occupation time, ideally several days or weeks, is also necessary for cyclical errors such as multipath to average out.

Just as for the repeat levelling and repeat gravimetry, very few long-occupation repeat GPS observations have been acquired on the Perth Basin. Landgate has provided information for its repeat GPS data archives, but most of these occupations are only for a few hours (and sometimes less). Nevertheless, we intend to reprocess these data to determine whether they can provide cross-validation of the subsidence determined by other geodetic techniques. However, we are not hopeful based on the inconclusive experience gained from the following example.

In 1999, Landgate occupied the tide-gauge benchmark (NMV/F/6A) near the Fremantle tide-gauge (PSMSL code 111; GLOSS code 53) with GPS for five days. This was part of a national project on heights (Johnston & Luton 2001). A tide-gauge benchmark is a stable point of reference for monitoring the height of the tide-gauge, and can also be used to maintain a more continuous time series of sea-level observations if there are changes to the tide-gauge instrumentation. Unfortunately, the NMV/F/6A benchmark has since been destroyed, but fortunately there are differential levelling connections to several nearby benchmarks. In 2010, a new ground mark was established with largely unobstructed sky views and seven days of GPS observations were collected by McMullan Nolan Group P/L land surveyors. Differential levelling to nearby benchmarks was also conducted, so there is a height connection between the GPS surveys.

We reprocessed these repeat GPS data using four independent software packages: Geoscience Australia's v1 AUSPOS service (http://www.ga.gov.au/geodesy/sgc/wwwgps/); Natural Resources Canada's CSRS (Canadian Spatial Reference System) service (http://ess.nrcan.gc.ca/2002_2006/gnd/csrs_e.php); Bernese v5.0 (Dach et al. 2007); and GIPSY-OASIS v5.0 (https://gipsy-oasis.jpl.nasa.gov/). Precise satellite orbits and other parameters from the International GNSS Service (IGS; Dow *et al.* 2009) and NASA's Jet Propulsion Laboratory (JPL) were used during the processing. The resulting ellipsoidal heights were in the ITRF2005 reference frame (Altamimi *et al.* 2007) and apply to the mean time-epoch of each GPS survey. This approach to GPS processing is quite different to using vendor packages, because of the more sophisticated modelling and processing techniques employed.

The results from this particular repeat GPS survey were inconclusive because, even using five to seven days of measurements, the GPS-determined ellipsoidal height near the Fremantle tide-gauge was determined, after height corrections for the different benchmarks, to be exactly the same in 2010 as it was in 1999. Assuming independence and the general law of propagation of the variances of each ellipsoidal height estimate at each time-epoch, the 'subsidence' over this period was (0±6) mm/yr. Within one-sigma error bounds, this is statistically consistent with the ~-5 mm/yr rate determined from the continuous GPS station at Gnangara (described next). Of course, there is also the possibility that the Fremantle tide-gauge is not subsiding or not at the same rate as Gnangara.

### Continuous GPS

The concept of continuous GPS (CGPS) is to continuously operate a GPS receiver and antenna mounted on a permanent ground monument to confer the benefit of regular GPS observations to monitor the 3D position of that station. A CGPS station at Gnangara (IGS code PERT) has operated in the Perth Basin since August 1993, well before the increased groundwater extraction from the Yarragadee Aquifer (Figure 1).

These data have been analysed by various scientists, including this study. For instance, Bouin & Wöppelman (2010) computed a vertical velocity of –5.21±0.73 mm/yr between January 1997 and November 2006, noting (p. 204) 'this may reflect a local subsidence of the GPS station, as this part of Australia is not susceptible to tectonic deformation'. The Gnangara CGPS station, though not installed to monitor groundwater-extraction-induced subsidence of the Perth Basin, provides the strongest evidence that there is subsidence in the northern suburbs of Perth. Also, it refutes the ~–50 mm/yr rate determined by Ng & Ge (2007) using InSAR.

Another CGPS was installed at Hillarys in 1997 as part of a project to monitor the height of tide-gauges in the Australian region. During the review cycle of this paper, we were granted access to these data by Geoscience Australia, but they are not in a form that can be readily analysed in a short time frame, particularly because of the multiple equipment changes that make the time series very discontinuous. Several CGPS stations across the Perth region have also been installed as part of a commercial venture (http://www.rtknetwest.com.au/), which can also be used to monitor the subsidence (Baldi *et al.* 2009). However, several of the monuments are not of 'geodetic quality', being located on buildings or metal masts.

We reprocessed the CGPS data from Gnangara using daily GPS data files archived by the IGS using the GIPSY v5.0 software in precise point positioning mode (Zumberge *et al.* 1997). This processing used fiducial-free satellite orbits, satellite clocks and Earth rotation parameters from JPL. The resulting ellipsoidal heights were transformed to the IGS realisation of the ITRF2005 reference frame (Altamimi *et al*. 2007). These are plotted in Figure 3 (bottom panel), which includes a moving-average fitted curve, the width of which was determined empirically so that the general shape of the fitted curve did not alter for an increased window. Figure 3 (top and central panels) also shows the change in water depth over the same time span from artesian monitoring bores AM30Y (WA Department of Water code 61615127) and AM30Z (WA Department of Water code 61615043), which respectively monitor the Yarragadee and Leederville Aquifers, and are located within ~3.5 km of the Gnangara CGPS station.

One-year periodic signals of varying amplitudes are superimposed on all time series in Figure 3. The seasonal signal in the GPS data (bottom panel) is better defined than for the borehole water-depth data (top and central panels), most likely because of the much higher frequency of measurements. However, the GPS data processing did not include modelling of atmospheric-pressure-loading effects, which can cause annual signals (Petrov & Boy 2004). The break in the time series at the start of 2001 was due to equipment malfunction. This type of discontinuity can be detrimental to the determination of reliable trends from CGPS. The increased noise in the CGPS time series beyond 2007 seems to correlate with the irregularities in the water depths in the Yarragadee and Leederville Aquifers, but this is only associative and not necessarily causative.

We used unweighted linear regression to determine the vertical velocity of the Gnangara CGPS installation for the entire 14 year time series (1997–2011), which gave a -4.6 mm/yr rate of subsidence (Table 1). This is slightly less than the rate of -5.2 mm/yr determined by Bouin & Wöppelman (2010) between 1997 and 2007. Looking at the bottom panel in Figure 3, Bouin & Wöppelman's estimate omits the four years where the rate of subsidence has reduced (Table 1). To test the effect of length of time series used in the regression, we computed linear subsidence rates for three subsets of the time series in Figure 3: before, during and after the increased ground water extraction (Table 1). We also calculated the linear rates of extraction from the Yarragadee and Leederville Aquifers at the AM30 boreholes (Table 1).

The results in Table 1 are somewhat more telling than a simple linear regression of the entire time series and fit with expectation. First, the Gnangara CGPS station is located only ~3.5 km from the AM30 boreholes, so it is reasonable to assume that there will be good correlation between the two sets of measurements. The subsidence rate of -5.4 mm/yr before 2000 is due to the previous groundwater extraction rate of around 5 m per decade, which has been inferred from the longer time series at AM27 (Figure 1). The land subsidence rate increases to -6.1 mm/yr during the period of increased groundwater extraction (around 20 m over five years at AM30Y; Figure 3 top panel). After the extraction was reduced in 2005, the subsidence rate drops to -1.9 mm/yr, but this value is more uncertain because of the increased noise in the CGPS time series after mid-2007 (bottom panel in Figure 3).

The problem with this CGPS data set is that it determines the subsidence at a discrete point, so only inferences can be made about what may be occurring in other parts of the Perth Basin. As already discussed, repeat levelling, gravimetry and GPS data are sparse and/or unusable. As such, a technique that is capable of mapping subsidence over large areas is attractive; InSAR is one such candidate.

### InSAR

Two separate radar images taken from the same satellite-borne sensor at two different times (on repeat orbits) are overlaid and the images are processed to produce interferograms. Any phase difference between two or more interferograms at the same point or 'pixel' may be interpreted as ground deformation. This is referred to as repeat-pass differential InSAR (DInSAR). For further details on the InSAR concept, see Hanssen (2001).

The observed deformation is along the radar line of sight (LoS) between the satellite's position at the time of image capture and the point on the ground. Thus, the observed deformation is a 3D displacement vector (latitude, longitude, height), but these components cannot, on their own, be resolved uniquely. Where vertical-only deformation is assumed (or indicated by levelling or GNSS) the LoS deformation can be projected into the vertical direction using the incidence angle of the LoS (angle between the local vertical and the LoS) (Hansson 2001 p. 162–163). Alternatively, methods such as combining interferograms from ascending and descending orbits have been used to resolve other components (Wright *et al*. 2004), although the north component remains inherently weaker on the assumption of a near-polar satellite orbit.

InSAR has been used successfully to detect ground deformation caused by earthquakes, faults and other tectonic processes (Massonnet *et al*. 1993), volcano deformation monitoring (Amelung *et al*. 2000), land

**Table 1** Linear subsidence rates for the Gnangara CGPS station and linear drawdown rates at AM30 for the Yarragadee and Leederville Aquifersover different time periods

| Time period | Subsidence rate (mm/yr) | | Yarragadee drawdown (m/yr) | Leederville drawdown (m/yr) |
|---|---|---|---|---|
| 1997–2007 | -5.2 | Bouin & Wöppelman (2010) | -2.54 | -0.42 |
| 1997–2011 | -4.6 | Entire 14-year time series | -2.12 | -0.34 |
| 1997–2000 | -5.4 | Before increased extraction | -1.19 | -1.53 |
| 2000–2005 | -6.1 | During increased extraction | -3.21 | +0.53 |
| 2005–2011 | -1.9 | After increased extraction | -0.09 | +0.06 |

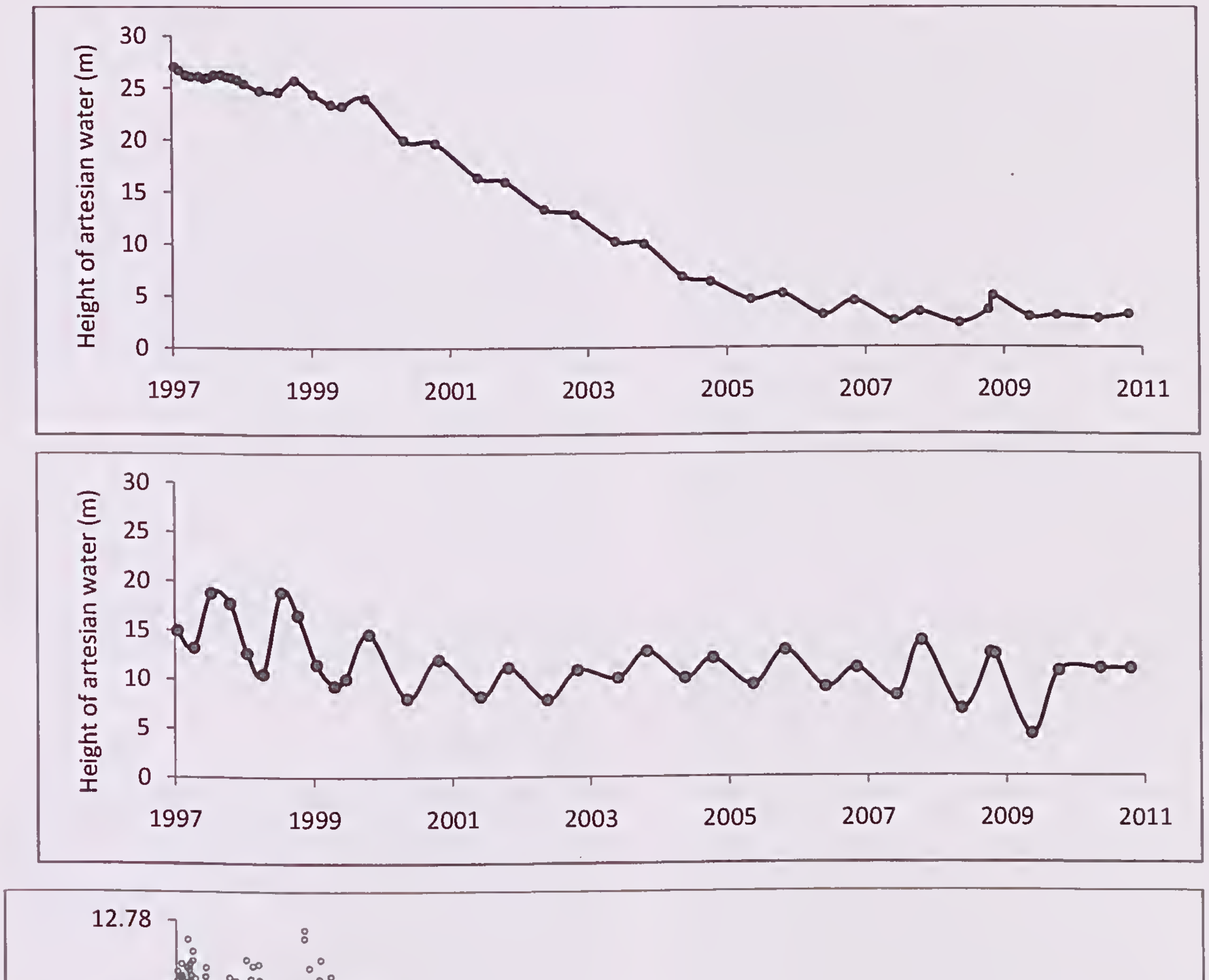


**Figure 3.** Top panel: change in height (in metres) of water in the Yarragadee Aquifer at AM30Y. Middle panel: change in height (in metres) of water in the Leederville Aquifer at AM30Z. Bottom panel: Time series of daily ellipsoidal height estimates (in metres) of the Gnangara CGPS station (IGS code PERT). Grey dots are the daily data points; black line is the moving average. See Table 1 for the rates and Figure 2 for the locations. Data courtesy of the WA Department of Water (http://www.water.wa.gov.au/Tools/Monitoring+and+data/default.aspx) and the IGS

subsidence due to water or hydrocarbon extraction (Galloway *et al.* 1998; Fielding *et al.* 1998) and cryospheric changes (Goldstein *et al.* 1993). The advantages of InSAR over other observation methods for detecting ground movement are high spatial resolution, the detection of sub-centimetre changes, and there are sometimes image archives over a study region. However, there are a number of restrictions on InSAR to map ground deformation. As described below, these are primarily due to spatial and temporal decorrelation and atmospheric refraction effects (Ferretti *et al.* 2001). Spatial decorrelation is caused by large distances (baselines) between the position of the satellite when the different radar images were observed (Zebker & Villasenor 1992). Temporal decorrelation occurs when the surface reflecting the radar signal within each pixel changes over time. Large temporal baselines between image pairs (e.g. several years) can cause temporal decorrelation in urban or built-up areas, while seasonal changes of vegetation usually result in total decorrelation in non-urbanised regions.

In addition, when the interferogram is coherent, variations in atmospheric conditions causing delay in the radar signal (Goldstein 1995) and errors in the satellite orbits and/or reference digital elevation model (DEM) can introduce additional artefacts into the interferometric phase. Processing multiple images in one 'stack' (Lyons & Sandwell 2003) can reduce atmospheric, orbital and DEM artefacts in the computed vertical velocities.

The InSAR method of persistent scatterers (PS) (Ferretti *et al.* 2001) uses stable backscattering characteristics from natural and man-made objects on the ground over long periods, often a number of years (Usai & Klees 1999), which can allow the detection of ground deformation where conventional DInSAR pairs would not necessarily be coherent. Different variants of the PS technique have been developed (Hooper *et al.* 2004; Kampes 2005), although these produce largely similar results (Sousa *et al.* 2011).

Dawson (2008) used InSAR to investigate vertical deformation in the Perth metropolitan region using (i) 13 ERS-1 and ERS-2 satellite images between 1992 and 1997; and (ii) five ENVISAT satellite images between 2005 and 2006. Interferograms were produced using the Doris processing software (Kampes & Usai 1999), with in-house software used for phase unwrapping and time series analysis (Dawson 2008), the latter being based on the Small BAseline Subset (SBAS) technique (Bernadino *et al.* 2002). The results from Dawson's (2008) study suggested subsidence rates of -3 mm/yr for 1992–1997, and -4 mm/yr for 2005–2006, but these are barely statistically significant because Dawson (2008 p. 185) indicated that -3 mm/yr is only just resolvable.

These InSAR subsidence rates are variable across the Perth metropolitan region but are consistent with our CGPS rates at Gnangara (Table 1). Preliminary results from our own InSAR processing (not yet ready for publication) suggest similar vertical velocities. Some care should be exercised when interpreting the 2005–2006 results from Dawson (2008), primarily because of the small number of ENVISAT images (five) available. However, Dawson's results from the 1992–1997 ERS-1 and ERS-2 images contradict the -50 mm/yr rate from Ng & Ge (2007) that was obtained from a similar set of images. Importantly, the independent CGPS supports the rate from Dawson (2008) and also refutes the rate from Ng & Ge (2007).

A limiting factor to InSAR investigations of the Perth Basin are gaps in the retrospective imagery record, as was also encountered by Dawson (2008). The incomplete record is due to the lack of a monitoring program in place at the time of the subsidence, as the satellites carrying the InSAR sensors were not programmed to acquire imagery over the Perth Basin. Hence, there is little retrospective InSAR imagery during the period of most interest (2000–2005), when large amounts of water were being extracted from Yarragadee Aquifer (Figures 1, 3).

In addition, the few images available are not necessarily captured at the same time of the year, which makes temporal decorrelation more likely. Multiple images during each year can detect seasonal height variations, such as expanding clays during wet months (Gabriel *et al.* 1989), which could then be separated from the subsidence signal. Specific acquisitions can be requested from the relevant space agencies for future work if a dedicated monitoring program is to be established in the Perth region.

## CONCLUSIONS

First, there is no independent supporting evidence for the -50 mm/yr subsidence reported by Ng & Ge (2007) and sensationalised by the Western Australia news media. Evidence from reprocessed InSAR imagery and independent CGPS suggest that the subsidence is closer to -5 mm/yr, but the exact values are spatially and temporally variable (Table 1).

We have described the difficulties involved in retrospectively quantifying and mapping subsidence in the Perth Basin when there was no monitoring program, particularly for small vertical velocities of only a few mm/yr. It appears that available InSAR and CGPS data are most likely to provide the better information on recent-past subsidence, although these are hampered by the low spatial resolution of CGPS and gaps in the recent-past InSAR record. Repeat gravity observations lack the required precision to detect these small vertical velocities, but it is possible that future repeat levelling and GPS campaigns may provide more supporting evidence.

There is good correlation between changes in the depth of the water table in the confined Yarragadee Aquifer and the rates of subsidence of the CGPS installation at Gnangara (Figure 3). Depending on the time-span chosen over which linear regression is applied, different subsidence rates can be obtained. Fourteen years of data give a subsidence rate of -4.6 mm/yr, but this increases to -6.1 mm/yr during the 2000–2005 period of increased groundwater extraction. This demonstrates that the rate of subsidence is not linear, which needs to be taken into account by GPS analysts who do not necessarily have such local knowledge (Bouin & Wöppelman 2010).

Perth will need a dedicated subsidence-monitoring program if future water shortages necessitate re-commencement of increased groundwater extraction from the Yarragadee Aquifer. This would also be necessary to correct relative sea-level change measurements at the Fremantle and Hillarys tide-gauges.

## ACKNOWLEDGEMENTS

WEF, MSF and LMM are supported under the ARC's Linkage Projects funding scheme (project number LP110100284). The views expressed herein are those of the authors and are not necessarily those of the ARC. We would like to thank Geoscience Australia, the Western Australian Department of Water, Landgate, the Geological Survey of Western Australia, Mr Gerry Nolan (McMullen Nolan Group P/L) and Jon Kirby (Curtin University) for providing data. We also thank Phil Collier and an anonymous reviewer for their constructive critiques.

## REFERENCES

Ackermann E 2006. Indicators of failed information epidemics in the scientific journal literature: a publication analysis of Polywater and Cold Nuclear Fusion. *Scientometrics* 66, 451–466, doi: 10.1007/s11192-006-0033-0.

Altamimi Z, Collilieux X, Legrand J, Garayt B & Boucher C 2007. ITRF2005: a new release of the International Terrestrial Reference Frame based on time series of station positions and Earth orientation parameters, *Journal of Geophysical Research, Solid Earth* **112**, B09401, doi: 10.1029/2007JB004949.

Amelung F, Jónsson S, Zebker H & Segall P 2000. Widespread uplift and 'trapdoor' faulting on Galapagos volcanoes observed with radar interferometry. *Nature* 407, 993–996, doi: doi:10.1038/35039604.

Angus-Leppan P V 1979. Refraction in levelling - its variation with ground slope and meteorlogical conditions. *Australian Journal of Geodesy, Photogrammetry and Surveying* 31, 27–41.

Aubrey D G & Emery K O 1986. Australia: an unstable platform for tide-gauge measurements of changing sea-level. *Journal of Geology* 94, 699–712.

Baldi P, Casula G, Cenni N, Loddo F & Pesci A 2009. GPS-based monitoring of land subsidence in the Po Plain (Northern Italy). *Earth and Planetary Science Letters* **288**, 204–212, doi:10.1016/j.epsl.2009.09.023.

Bawden G W, Thatcher W, Stein R S, Hudnut K W & Peltzer G 2001. Tectonic contraction across Los Angeles after removal of groundwater pumping effects. *Nature* **412**, 812–815, doi:10.1038/35090558.

Belperio A P 1993. Land subsidence and sea-level rise in the Port Adelaide estuary: implications for monitoring the greenhouse effect. *Australian Journal of Earth Sciences* **40**, 359–368, doi: 10.1080/08120099308728087.

Bernadino P, Fornaro G, Lanari R & Sansosti E 2002. A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms. *IEEE Transactions on Geoscience and Remote Sensing* 40, 2375–2383, doi: 10.1109/TGRS.2002.803792.

Biró P 1983. *Time variation of height and gravity*. Wichmann, Karlsruhe.

Bouin M N & Wöppelmann G 2010. Land motion estimates from GPS at tide-gauges: a geophysical evaluation. *Geophysical Journal International* **180**, 193–209, doi: 10.1111/j.1365-246X.2009.04411.x.

Brunn P 1988. The Brunn Rule of erosion by sea-level rise: a discussion on large-scale two-and three-dimensional usages. *Journal of Coastal Research* 4, 627–648.

Chen K-H, Yang M, Huang Y-T, Ching K-E & Rau R-J 2011. Vertical displacement rate field of Taiwan from geodetic levelling data 2000–2008. *Survey Review* 43, 296–302, doi: 10.1179/003962611X13055561708380.

Chi S C & Reilinger R E 1984. Geodetic evidence for subsidence due to groundwater withdrawal in many parts of the United States of America. *Journal of Hydrology* 67, 155–182, doi: 10.1016/0022-1694(84)90239-7.

Church J A & White N J 2006. A 20th century acceleration in global sea-level rise. *Geophysical Research Letters* **33**, L01602, doi: 10.1029/2005GL024826.

Coates R J, Frey H, Mead G D & Bosworth J M 1985. Space-age geodesy: the NASA crustal dynamics project. *IEEE Transactions on Geoscience and Remote Sensing* 23, 360–368, doi: 10.1109/TGRS.1985.289425.

Craymer M R & Vaníček P 1986. Further analysis of the 1981 Southern California field test for levelling refraction. *Journal of Geophysical Research* 91(B9), 9045–9055, doi:10.1029/JB091iB09p09045.

Dach R, Hugentobler U, Fridez P & Meindl M (Editors) 2007. Bernese GPS software version 5.0, Astronomical Institute, University of Bern, Switzerland.

Dawson J H 2008. Satellite radar interferometry with application to the observation of surface deformation in Australia. PhD thesis, Australian National University, Canberra (unpubl.).

Dow J M, Neilan R E & Rizos C 2009. The International GNSS Service (IGS) in a changing landscape of Global Navigation Satellite Systems. *Journal of Geodesy* **83**, 191–198, doi: 10.1007/s00190-008-0300-3.

Featherstone W E 2008. Geodesy. *In:* Kemp K K (ed.) *Encyclopaedia of Geographic Information Science*, pp. 171–176. SAGE Publications, Thousand Oaks.

Ferretti A, Prati C & Rocca F 2001. Permanent scatterers in SAR interferometry. *IEEE Transactions on Geoscience and Remote Sensing* **39**, 8–20, doi: 10.1109/IGARSS.1999.772008.

Fielding E J, Blom R G & Goldstein R M 1998. Rapid subsidence over oil fields measured by SAR. *Geophysical Research Letters* **25**, 3215–3218, doi: 10.1029/98GL52260.

Filmer M S & Featherstone W E 2009. Detecting spirit-levelling errors in the AHD: recent findings and some issues for any new Australian height datum. *Australian Journal of Earth Sciences* **56**, 559–569, doi: 10.1080/08120090902806305.

Gabriel A K, Goldstein R M & Zebker H A 1989. Mapping small elevation changes over large areas: differential radar interferometry. *Journal of Geophysical Research* 94, 9183–9191, doi: 10.1029/JB094iB07p09183.

Galloway D L, Hudnut K W, Ingebritsen S E, Phillips S P, Peltzer G, Rogez F & Rosen P A 1998. Detection of aquifer system compaction and land subsidence using interferometric synthetic aperture radar, Antelope Valley, Mojave Desert, California. *Water Resources Research* 34, 2573–2585, doi: 10.1029/98WR01285.

Goldstein R 1995. Atmospheric limitations to repeat-pass radar interferometry. *Geophysical Research Letters* **22**, 2517–2520, doi: 10.1029/95GL02475.

Goldstein R M, Engelhardt H, Kamb B & Frolich R M 1993. Satellite radar interferometry for monitoring ice sheet motion: application to an Antarctic ice stream. *Science* 262, 1525–1530, doi: 10.1126/science.262.5139.1525.

Hanssen R F 2001. *Radar interferometry data interpretation and error analysis*. Springer, Berlin.

Hooper A, Zebker H, Segall P & Kampes B 2004. A new method for measuring deformation on volcanoes and other natural terrains using InSAR persistent scatterers. *Geophysical Research Letters* **31**, L23611, doi: 10.1029/2004GL021737.

Hwang C, Cheng T-C, Cheng C C & Hung W C 2010. Land subsidence using absolute and relative gravimetry: a case study in central Taiwan. *Survey Review* **42**, 27–39, doi:10.1179/003962609X451672.

ICSM 2007. Standards and practices for control surveys (version 1.7). Inter-Governmental Committee on Surveying and

Mapping, Canberra, http://www.icsm.gov.au/icsm/publications/sp1/sp1v1-7.pdf

Jakica S, Quigley M C, Sandiford M, Clark D, Fifield L K & Alimanovic K 2011. Geomorphic and cosmogenic nuclide constraints on escarpment evolution in an intraplate setting, Darling Escarpment, Western Australia. *Earth Surface Processes and Landforms* 36, 449–459, doi: 10.1002/esp.2058.

Johnston G M & Luton G C 2001. GPS and the Australian Height Datum. Proceedings 5th International Symposium on Satellite Navigation Technology and Applications, Canberra, July 2001 (CD ROM).

Kampes B M 2005. Displacement parameter estimation using permanent scatterer interferometry. PhD thesis, Delft University of Technology, Delft (unpubl.).

Kampes B & Usai S 1999. Doris: the Delft object-oriented radar interferometric software. Proceedings ITC 2nd ORS Symposium, August 1999.

Kearsley A H W, Ahmad Z & Chan A 1993. National height datums, levelling, GPS heights and geoids. *Australian Journal of Geodesy, Photogrammetry and Surveying* **59**, 53–88.

Kirby J F 2003. On the combination of gravity anomalies and gravity disturbances for geoid determination in Western Australia. *Journal of Geodesy* **77**, 433–439, doi: 10.1007/s00190-003-0334-5

Lyons S & Sandwell D 2003. Fault creep along the southern San Andreas from interferometric synthetic aperture radar, permanent scatterers, and stacking. *Journal of Geophysical Research* **108**, 2047–2070, doi: 10.1029/2002JB001831.

Massonnet D, Rossi M, Carmona C, Adragna F, Peltzer G, Fiegl K & Rabaute T 1993. The displacement field of the Landers earthquake mapped by radar interferometer. *Nature* **364**, 138–142, doi: 10.1038/364138a0.

Morgan P 1992. An analysis of the Australian Height Datum: 1971. *The Australian Surveyor* 37, 46–63.

Moritz H 1980. Geodetic Reference System 1980. *Bulletin Géodésique* **54**, 395–405, doi: 10.1007/BF02521480

Mörner N-A 2004. Estimating future sea-level changes from past records. *Global and Planetary Change* 40, 49–54, doi: 10.1016/S0921-8181(03)00097-3.

Ng A H N & Ge L 2007. Application of persistent scatterer in InSAR and GIS for urban subsidence monitoring. Proceedings IEEE International Geoscience & Remote Sensing Symposium, Barcelona, July, paper 1296.

Petrov L & Boy J-P 2004. Study of the atmospheric pressure loading signal in very long baseline interferometry observations. *Journal of Geophysical Research – Solid Earth* **109**, B03405, doi: 10.1029/2003JB002500.

Roelse A, Granger H W, Graham J W 1975. The adjustment of the Australian levelling survey 1970 – 1971 (2nd edition). Division of National Mapping, Canberra Technical Report 12.

Rothacher M 2002. Estimation of station heights with GPS. *In:* Drewes H, Dodson A H, Fortes L P S, Sanchez L & Sandoval P (eds), *Vertical reference systems*, pp. 81–90. Springer, Berlin.

Sousa J J, Hooper A J, Hanssen R F, Bastos L C & Ruiz A M 2011. Persistent Scatterer InSAR: a comparison of methodologies based on a model of temporal deformation vs. spatial correlation selection criteria. *Remote Sensing of Environment* **115**, 2652–2663, doi:10.1016/j.rse.2011.05.021.

Torge W 1989. *Gravimetry*. de Gruyter, Berlin

Usai S & Klees R 1999. SAR interferometry on a very long time scale: a study of the interferometric characteristics of man-made features. *IEEE Transactions on Geoscience and Remote Sensing* 37, 2118_2123, doi: 10.1109/36.774730.

Vaníček P., Castle R O, Balazs E I 1980. Geodetic leveling and its applications. *Reviews of Geophysics and Space Physics* 18, 505–524, doi: 10.1029/RG018i002p00505.

Wellman P & Tracey R 1987. South-west seismic zone of Western Australia: measurement of vertical ground movements by repeat levelling and gravity surveys. *BMR Journal of Geology and Geophysics* 10, 225–232.

Wright T J, Parsons B E & Lu Z 2004. Towards mapping surface deformation in three dimensions using InSAR. *Geophysical Research Letters* 3, L01607, doi: 10.1029/2003GL018827.

Zebker H A & Villasenor J 1992. Decorrelation in interferometric radar echoes. *IEEE Transactions on Geoscience and Remote Sensing* 30, 950–959, doi: 10.1109/36.175330.

Zerbini S, Richter B, Rocca F, Van Dam T & Matonti F 2007. A combination of space and terrestrial geodetic techniques to monitor land subsidence: case study, the Southern Po Plain, Italy. *Journal of Geophysical Research* **112**, B05401, doi: 10.1029/2006JB004338.

Zumberge J F, Heflin M B, Jefferson D C, Watkins M M & Webb F H 1997. Precise point positioning for the efficient and robust analysis of GPS data from large networks. *Journal of Geophysical Research – Solid Earth* **102**, 5005–5017, doi: 10.1029/96JB03860

*Manuscript received 10 January 2012; accepted 27 March 2012*

Journal of the Royal Society of Western Australia, 95: 63–77, 2012

# Three decades of cetacean strandings in Western Australia: 1981 to 2010

C J GROOM[1] & D K COUGHRAN[2]

[1] *Species and Communities Branch, Department of Environment and Conservation, Locked Bag 104, Bentley Delivery Centre WA 6983* ✉ *christine.groom@dec.wa.gov.au*

[2] *Nature Protection Branch, Department of Environment and Conservation, Locked Bag 104, Bentley Delivery Centre WA 6983* ✉ *douglas.coughran@dec.wa.gov.au (Corresponding author)*

Western Australia has an extensive coastline that provides a range of marine habitats for cetaceans. This paper constitutes the first comprehensive review of cetacean strandings in the region. From 1981 to 2010, stranding events were reported to the Western Australian Department of Environment and Conservation and recorded in the Western Australian Cetacean Stranding Database. During this period a total of 732 cetacean stranding events have been recorded, involving 34 species and 1753 individuals. Bottlenose dolphins (*Tursiops* sp.) were involved in the most stranding events (n = 330), while long-finned pilot whales (*Globicephala melas*) accounted for the largest number of individuals (n = 446 individuals involved in 22 stranding events). The southwest of the State is the region with the greatest number of reported stranding events. Sixty percent of stranded individuals were found alive. Over 70% of stranded cetaceans found alive were returned to deeper water.

**KEYWORDS: cetacean, dolphin, stranding, Western Australia, whale.**

## INTRODUCTION

The coast of Western Australian stretches for 12 889 km (excluding islands), covers a wide latitudinal range and includes a range of marine habitats. Western Australia has the most diverse cetacean fauna of all Australian states with 37 species confirmed to be present (Bannister *et al.* 1996). With such an extensive coastline many sick, injured or dead cetaceans are encountered each year.

Prior to 1981 there was no formal process in place to maintain accurate records of stranding events in Western Australia and only a portion of events were captured through specimen records of the Western Australian Museum. In 1982 the Western Australian Cetacean Stranding Database was created. Reports of cetacean incidents (i.e. stranding, entanglement, ship/vessel strike etc) on the Western Australian coast are now routinely made to the Western Australian Department of Environment and Conservation (DEC) and recorded in the database. The department is responsible for administration of the Wildlife Conservation Act 1950 and managing issues relevant to fauna as defined under the Act, which includes whales and dolphins (cetaceans). In this capacity, DEC staff attend strandings either to investigate the cause of death of animals or to assess the live animals to determine what action, if any, is required (e.g. rescue attempt, euthanasia) and consequently are the major source of information in the database. In a small number of cases information was obtained from other government officers (e.g. officers from the Department of Fisheries), or from members of the public. The data presented here do not include records of healthy uncompromised animals that were sighted frequenting Western Australian waters and required no assistance or intervention. Skeletal and DNA materials are made available to the Western Australian Museum (WAM) but those records maintained at WAM are not as comprehensive as those received and validated by the DEC. Reports of incidents received by WAM are referred back to DEC in accordance with the Wildlife Conservation Act 1950.

Stranded cetaceans provide a unique opportunity to collect DNA, tissue samples, morphometric data and demographic data that contribute to our knowledge of the biology of these species. There are some species which are known only from stranded specimens (e.g. Andrew's beaked whale, *Mesoplodon bowdoini*) (MacLeod *et al.* 2006). Assessments of strandings have been used for a number of purposes including determining baseline mortality trends for assessing population health (Bogomolni *et al.* 2010), assessing the impact of human interaction on cetaceans (Kemper *et al.* 2005), assessing the impact of increased water temperature on cetacean communities (MacCleod *et al.* 2005) and obtaining information on the distribution, biology and ecology of species.

Limited information has been published on cetacean strandings along the coast of Western Australia. Those articles that have been published relate to particular stranding events (Anonymous 1981; Edwards 1987; McNamara 1987; Mell 1988; Gales 1992) or a particular taxonomic group (e.g. beaked whales: D K Coughran unpubl. data). Basic stranding data from Western Australia have also been included in general assessments of the conservation needs of cetacean species (Bannister *et al.* 1996). However, a comprehensive review of strandings in the region has not previously been undertaken.

This study aims to describe the cetacean fauna of Western Australia based on the stranding record, identify patterns in the spatial and temporal distribution of stranding events and assess the outcomes of stranding events (died, returned to deeper water etc). We also discuss the conservation and management implications of the findings.

## METHODS

In Western Australia, any observations of stranded cetaceans that require some form of management are reported to DEC and an appropriate response is initiated ranging from noting the report to a full-scale rescue operation. The events and their outcomes are recorded in the Western Australian Cetacean Stranding Database and the records in this database were used for this study. These reports are investigated and validated by DEC before entry into the database by the database custodian who has maintained the database since it was created. Records of cetaceans recorded between 1981 and 2010 (29 years) are analysed here.

For the purposes of this paper a stranding may be defined as any event involving the beaching or washing up onshore of live or dead cetaceans, but also includes dead cetaceans floating within State waters (i.e. up to three nautical miles offshore). Incidents where some individuals from a group stranded and the rest were behaving in a manner that suggested they too would strand without intervention were also considered stranded. This is similar to other studies that refer to out-of-habitat or near-mass strandings also being included in analyses of strandings (Aragones *et al*. 2010). Each record in the database represents a single event. Each event may involve multiple individuals as it is not uncommon for a cow and calf to strand together or, for some species, an entire group to mass strand. A mass stranding was defined as any event involving three or more individuals of the same species. This approach means that mother–calf pairs are not included as mass strandings. It was sometimes difficult to decide if an event was a mass stranding or separate unrelated individual strandings if there was significant spatial (e.g. 20 km) and/or temporal (i.e. multiple days)spread between individuals or reports. For large mass-stranding events it was sometimes not possible to accurately count the number of individuals, particularly for events involving tens or hundreds of individuals, and so for these events the numbers reported should be considered estimates. Records where species identification was uncertain have been excluded from the study.

We categorised the outcome of stranding events in terms of the fate of individuals. The existing database does not clearly store this information and so notes in comments fields and the original paper records were consulted to assign individuals to an outcome category. Each individual was assigned to one category only, although events involving multiple individuals meant that different individuals from the one event may have been assigned to different outcomes (e.g. a mass-stranding event where some individuals died whilst others were returned to deeper water). The categories used were: found dead; died; euthanased; returned to deeper water; restranded and died; restranded and euthanased; restranded and returned to deeper water; taken into care and died; taken into care and returned to deeper water; and unknown. Those categorised as 'returned to deeper water' had either involved a rescue operation or tidal changes had occurred enabling the animals to refloat and return to deeper water. Those categorised as restranded had been returned to deeper water but had subsequently returned to shore and therefore required further intervention. We did not examine the information recorded for stranding events to identify possible causes of stranding. For records where a total length measurement was recorded, an age category was allocated to each individual based on age/length species information (Bannister *et al*.1996).

We analysed spatial and temporal trends in the number of strandings. The spatial distribution of strandings was summarised in relation to the Integrated Marine and Coastal Regionalisation of Australia (IMCRA) meso-scale bioregions. The bioregions were developed to provide a framework for planning resource development and biodiversity conservation (Commonwealth of Australia 2006). These bioregions are referred to in managing fisheries and in planning a comprehensive and representative marine reserve system. For those stranding records occurring along rivers or in estuarine environments, they were allocated to the nearest IMCRA region. The seasonality of stranding records was assessed by investigating the number of records by month for each species with more than 20 records. Pearson's chi-squared test was used to determine whether the stranding frequency varied significantly by season.

To aid discussion, we grouped species that stranded into four broad categories: dolphins, toothed whales, baleen whales and beaked whales (Table 1). The taxonomic group Delphinidae has some members that have been allocated to 'dolphins' and others to 'toothed whales'.

The taxonomy used in this paper follows Bannister *et al*. (1996). The taxonomy of bottlenose dolphins around the world is confused by the identification of 'nearshore' and 'offshore' populations that have shown morphological and genetic differences (Hoelzel *et al*. 1998; Hale *et al*. 2000; Wang *et al*. 2000). A new species of inshore bottlenose dolphin was described in 2011 from a very small geographic area of southeastern Australia (Charlton-Robb *et al*. 2011) indicating that the taxonomy of bottlenose dolphin is even more complex. The taxonomy of bottlenose dolphin records in the database is not known and so individual stranding events were classified as *Tursiops* sp.

## RESULTS

### Species, demographics and event types

A total of 732 cetacean stranding events were recorded along the Western Australian coast between 1981 and 2010, involving 34 species and 1753 individuals (Table 1). For most species, records included stranded individuals from both sexes and from multiple age-classes. Most stranding events involved single animals (n = 681, 93%). Twenty-three events (3%) involved groups of two animals and 32 events (4%) were of three or more (Table 2). Mass strandings (i.e. three or more individuals) were recorded for 11 species. Fifty-nine percent (n = 1034) of the total number of stranded individuals were involved in mass strandings. False killer whales (*Pseudorca crassidens*), long-finned pilot whales (*Globicephala melas*), short-finned pilot whales (*Globicephala macrorhynchus*) and striped dolphins (*Stenella coeruleoalba)* have all mass stranded with more than 20 animals. Only one mixed species mass stranding was recorded during the time

**Table 1** Species (grouped by family), sex and age category of individual cetaceans stranded in Western Australia from 1981 to 2010.

| Common name | Scientific name | No. of individuals | No. of events | Individuals (sex) | | | Individuals (age category) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | M | F | ? | A | SA | C | ? |
| **Delphinidae** | | | | | | | | | | |
| DOLPHINS | | | | | | | | | | |
| Indo-Pacific humpback dolphin | *Sousa chinensis* | 5 | 5 | 4 | - | 1 | 1 | 1 | 2 | 1 |
| Bottlenose dolphin | *Tursiops* spp. | 371 | 330 | 180 | 103 | 88 | 83 | 98 | 115 | 75 |
| Pantropical spotted dolphin | *Stenella attenuata* | 7 | 2 | 3 | 4 | - | 3 | 4 | - | 7 |
| Striped dolphin | *Stenella coeruleoalba* | 97 | 27 | 15 | 7 | 75 | 13 | 9 | 3 | 72 |
| Spinner dolphin | *Stenella longiristris* | 6 | 6 | 1 | 3 | 2 | 5 | - | - | 1 |
| Common dolphin | *Delphinus delphis* | 30 | 28 | 17 | 5 | 8 | 15 | 3 | 6 | 6 |
| Fraser's dolphin | *Lagenodelphis hosei* | 1 | 1 | 1 | - | - | - | 1 | - | - |
| Risso's dolphin | *Grampus griseus* | 2 | 2 | - | 2 | - | - | 1 | 1 | - |
| TOOTHED WHALES | | | | | | | | | | |
| Melon-headed whale | *Peponocephala electra* | 1 | 1 | - | - | 1 | 1 | - | - | - |
| Pygmy killer whale | *Feresa attenuata* | 1 | 1 | 1 | - | - | - | 1 | - | - |
| False killer whale | *Pseudorca crassidens* | 397 | 18 | 6 | 6 | 385 | 6 | 7 | - | 384 |
| Killer whale | *Orcinus orca* | 8 | 2 | 1 | 2 | 5 | 1 | - | 2 | 5 |
| Short-finned pilot whale | *Globicephala macrorhynchus* | 52 | 7 | 1 | 2 | 48 | 10 | 2 | 1 | 39 |
| Long-finned pilot whale | *Globicephala melas* | 446 | 22 | 23 | 15 | 408 | 20 | | 9 | 417 |
| **Physeteridae** | | | | | | | | | | |
| Sperm Whale | *Physeter macrocephalus* | 57 | 36 | 12 | 14 | 31 | 15 | 2 | 6 | 34 |
| **Kogiidae** | | | | | | | | | | |
| Pygmy sperm whale | *Kogia breviceps* | 18 | 18 | 3 | 8 | 7 | 8 | 2 | 8 | - |
| Dwarf sperm whale | *Kogia simus* | 5 | 4 | - | 4 | 1 | 2 | 3 | - | - |
| BALEEN WHALES | | | | | | | | | | |
| **Balaenidae** | | | | | | | | | | |
| Southern right whale | *Eubalaena australis* | 6 | 6 | 1 | 2 | 3 | 3 | | 1 | 2 |
| **Neobalaenidae** | | | | | | | | | | |
| Pygmy right whale | *Caperea marginata* | 6 | 6 | 3 | 1 | 2 | 2 | 2 | 1 | 1 |
| **Balaenopteridae** | | | | | | | | | | |
| Minke whale | *Balaenoptera acutorostrata* | 22 | 22 | 4 | 7 | 11 | - | 3 | 15 | 4 |
| Bryde's whale | *Balaenoptera edeni* | 1 | 1 | - | - | 1 | - | 1 | - | - |
| Blue whale | *Balaenoptera musculus* | 1 | 1 | 1 | - | - | 1 | - | - | - |
| Pygmy blue whale | *Balaenoptera musculus brevicauda* | 4 | 4 | 1 | 3 | - | 4 | - | - | - |
| Fin whale | *Balaenoptera physalus* | 2 | 2 | 1 | 1 | - | 1 | 1 | - | - |
| Humpback whale | *Megaptera novaeangliae* | 139 | 138 | 42 | 27 | 70 | 24 | 22 | 81 | 12 |
| BEAKED WHALES | | | | | | | | | | |
| **Ziphiidae** | | | | | | | | | | |
| Cuvier's beaked whale | *Ziphius cavirostris* | 4 | 4 | - | 2 | 2 | - | 3 | - | 1 |
| Arnoux's beaked whale | *Berardius arnuxii* | 1 | 1 | 1 | - | - | 1 | - | - | - |
| Shepherd's beaked whale | *Tasmacetus shepherdi* | 4 | 2 | - | 1 | 3 | 1 | - | - | 3 |
| Andrew's beaked whale | *Mesoplodon bowdoini* | 2 | 2 | 2 | - | - | - | 1 | 1 | - |
| Blainville's beaked whale | *Mesoplodon densirostris* | 1 | 1 | 1 | - | - | - | 1 | - | - |
| Gray's beaked whale | *Mesoplodon grayi* | 40 | 22 | 11 | 15 | 14 | 7 | 6 | 14 | 13 |
| Hector's beaked whale | *Mesoplodon hectori* | 2 | 2 | - | 2 | - | 1 | 1 | - | - |
| Strap-toothed beaked whale | *Mesoplodon layardii* | 8 | 4 | 2 | - | 6 | 2 | - | 1 | 5 |
| True's beaked whale | *Mesoplodon mirus* | 6 | 4 | 4 | 2 | - | 1 | - | 3 | 2 |
| | TOTAL: | **1753** | **732** | **342** | **238** | **1172** | **231** | **175** | **270** | **1084** |

A, adult; SA, subadult; C, calf; ?, not recorded or could not be determined in the field.

period considered in this study. It occurred at Hamelin Bay in March 2009 and involved 87 long-finned pilot whales and five bottlenose dolphins. There is an unusual record of two humpback whales stranding together at the Abrolhos Islands. These individuals were caught in a lagoon and were both returned to deeper water when the tide changed.

The largest mass stranding involved at least 320 long-finned pilot whales that came into the shallows at Dunsborough. This number was estimated from aerial photographs of the incident when 19 individuals came ashore and died and the rest of the pod were also expected to have stranded without the fast response and persistence of rescuers to herd the pod back to deeper waters.

Species that rarely stranded (less than five records) were Risso's dolphin (*Grampus griseus*), Fraser's dolphin (*Lagenodelphis hosei*), pygmy blue whale (*Balaenoptera*

**Table 2** Cetacean stranding events along the Western Australian coast for species that had stranding events involving more than one animal between 1981 and 2010. Events involving three or more individuals are considered mass strandings.

| Species | Number of individuals | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3–5 | 6–10 | 11–20 | 21–50 | 51–100 | 101–320+ |
| **Delphinidae** | | | | | | | | |
| Bottlenose dolphin | 313 | 11 | 3 | 3 | - | - | - | - |
| Pantropical spotted dolphin | 1 | - | - | 1 | - | - | - | - |
| Striped dolphin | 22 | 1 | 1 | 1 | - | 2 | - | - |
| Common dolphin | 26 | 2 | - | - | - | - | - | - |
| False killer whale | 12 | 1 | 1 | - | - | - | 2 | 2 |
| Killer whale | 1 | - | - | 1 | - | - | - | - |
| Short-finned pilot whale | 5 | - | - | 1 | - | 1 | - | - |
| Long-finned pilot whale | 18 | 1 | - | - | 1 | - | 1 | 1 |
| **Physeteridae** | | | | | | | | |
| Sperm whale | 33 | - | 1 | 2 | - | - | - | - |
| **Kogiidae** | | | | | | | | |
| Dwarf sperm whale | 3 | 1 | - | - | - | - | - | - |
| **Balaenopteridae** | | | | | | | | |
| Humpback whale | 138 | 1 | - | - | - | - | - | - |
| **Ziphiidae** | | | | | | | | |
| Shepherd's beaked whale | 1 | - | 1 | - | - | - | - | - |
| Gray's beaked whale | 14 | 3 | 4 | 1 | - | - | - | - |
| Strap-toothed beaked whale | 3 | - | 1 | - | - | - | - | - |
| True's beaked whale | 2 | 2 | - | - | - | - | - | - |

*musculus brevicauda*), pygmy sperm whale (*Kogia breviceps*), dwarf sperm whale (*Kogia simus*), Arnoux's beaked whale (*Berardius arnuxii*), Blainville's beaked whale (*Mesoplodon densirostris*) and Hector's beaked whale (*Mesolpodon hectori*). Many of these species are considered rare but some simply do not strand often (e.g. pygmy blue whale). Dolphins were involved in the largest number of events (401) whereas beaked whales were involved in the fewest events (42). The species that accounted for the most stranding events was the bottlenose dolphin (330), whilst the long-finned pilot whale accounted for the most individuals (446).

Thirty-four species were recorded as stranded during this study including three species not recorded by Bannister *et al.* (1996) bringing the total number of species recorded for Western Australia to 40. The additional species were Fraser's dolphin, pygmy blue whale and Hector's beaked whale.

The demographics of stranded cetaceans are shown in Table 1. There is a male bias in strandings of dolphins in the Delphinidae group with 64% of those sexed being male (n = 343). Individual species that demonstrated a clear male bias in stranding were humpback whales (61%, n = 69) and bottlenose dolphins (64%, n = 283). There was some evidence that bottlenose dolphins sometimes stranded in all-male groups, with two strandings of all-male groups of four and 10 individuals in the Mandurah Region. Sex and length (and therefore age) were recorded for only a small proportion of stranded toothed whales, 12 and 13%, respectively.

Among baleen whales, calves accounted for 60% of the individuals for whom length was measured or estimated (and therefore age could be estimated). A bias towards more calves stranding was observed for a number of species. Calves accounted for 31% of bottlenose dolphin strandings, 58% of humpback whale (*Megaptera novaeangliae*) strandings, 68% of minke whale (*Balaenoptera acutorostrata*) strandings and 35% of Gray's beaked whale (*Mesoplodon grayi*) strandings. For stranded sperm whales (Physeteridae and Kogiidae), 54% of strandings were considered adults based on length.

### Spatial distribution of strandings

Stranding events recorded in the database were not evenly distributed along the Western Australian coastline (Figure 1). The greatest density of strandings were recorded close to areas of high human population density. Very few strandings have been recorded from the Kimberley, Pilbara and Nullabor coasts.

A large number of bottlenose dolphin and humpback whale strandings have been recorded in the database so it was considered useful to investigate any spatial trends observed in these data separately. These two species collectively account for almost two thirds (n = 468 of 732, 63.9%) of stranding events (45.1% and 18.9% for each species, respectively).

The majority of bottlenose dolphin records were from the Swan River, Mandurah Estuary/Peel Inlet and Bunbury harbour areas and the coastline in between (Figure 2). Woodman Point was also a common place for bottlenose dolphin to strand. There were several records from Shark Bay where there has been ongoing research into bottlenose dolphins for many years and a general public interest because of the group of dolphins habituated to being fed at Monkey Mia.

Humpback whales have a geographical spread of records similar to bottlenose dolphins but are less concentrated between Perth and Mandurah (Figure 3). A cluster of 15 humpback whale strandings occurred along the 28km length of coast between Marmion and Alkimos and another cluster of six strandings along a 14km length of coast between Wedge Island and Lancelin. The North

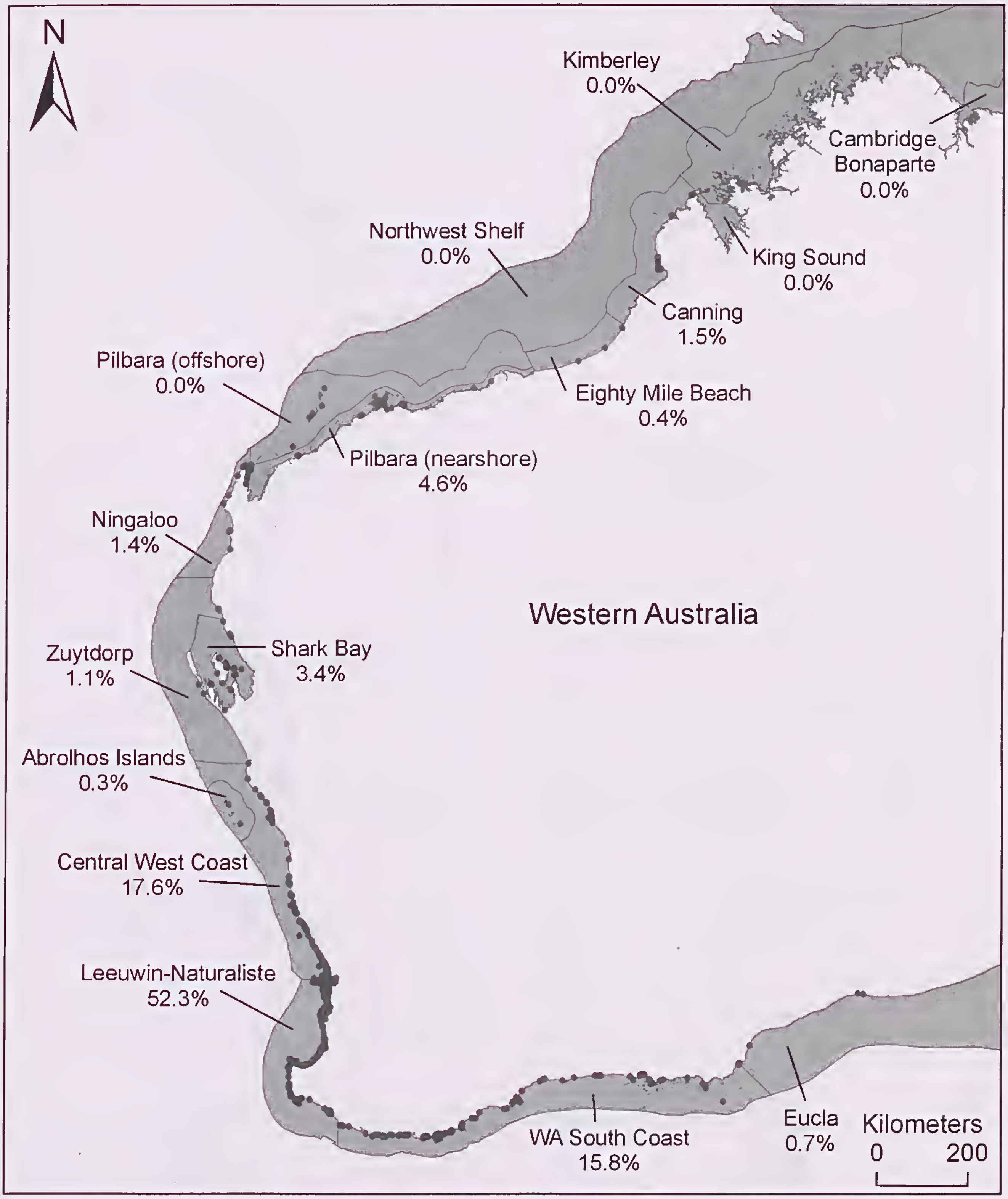


**Figure 1.** Distribution of cetacean stranding records in Western Australia summarised by Integrated Marine and Coastal Regionalisation of Australia meso-scale bioregions, 1981–2010.

West Cape, particularly the northern third of the peninsula, also accumulated a cluster of strandings with eight records for the area.

Most mass strandings have occurred in the vicinity of Busselton and Augusta in the southwest Capes region (Figure 4). In addition, four mass strandings of bottlenose dolphins have occurred in the Mandurah area together with more than 40 strandings of individuals or mother and calf pairs making it a common area for bottlenose dolphin strandings. These strandings are predominantly associated with spring tides, the dolphins being caught in shallow water or on mudflats of the estuary.

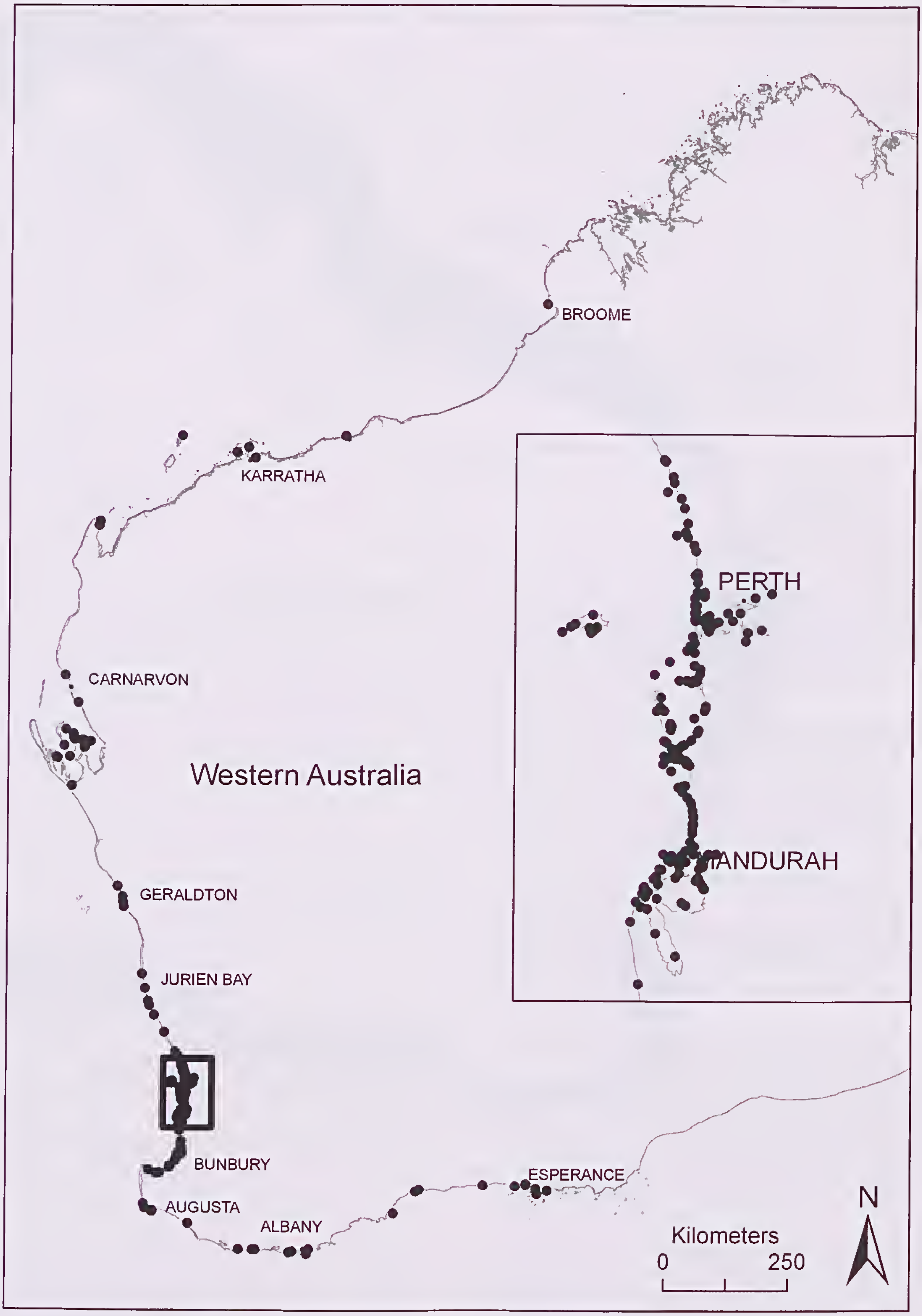


**Figure 2.** Distribution of bottlenose dolphin strandings from Western Australia 1981–2010.

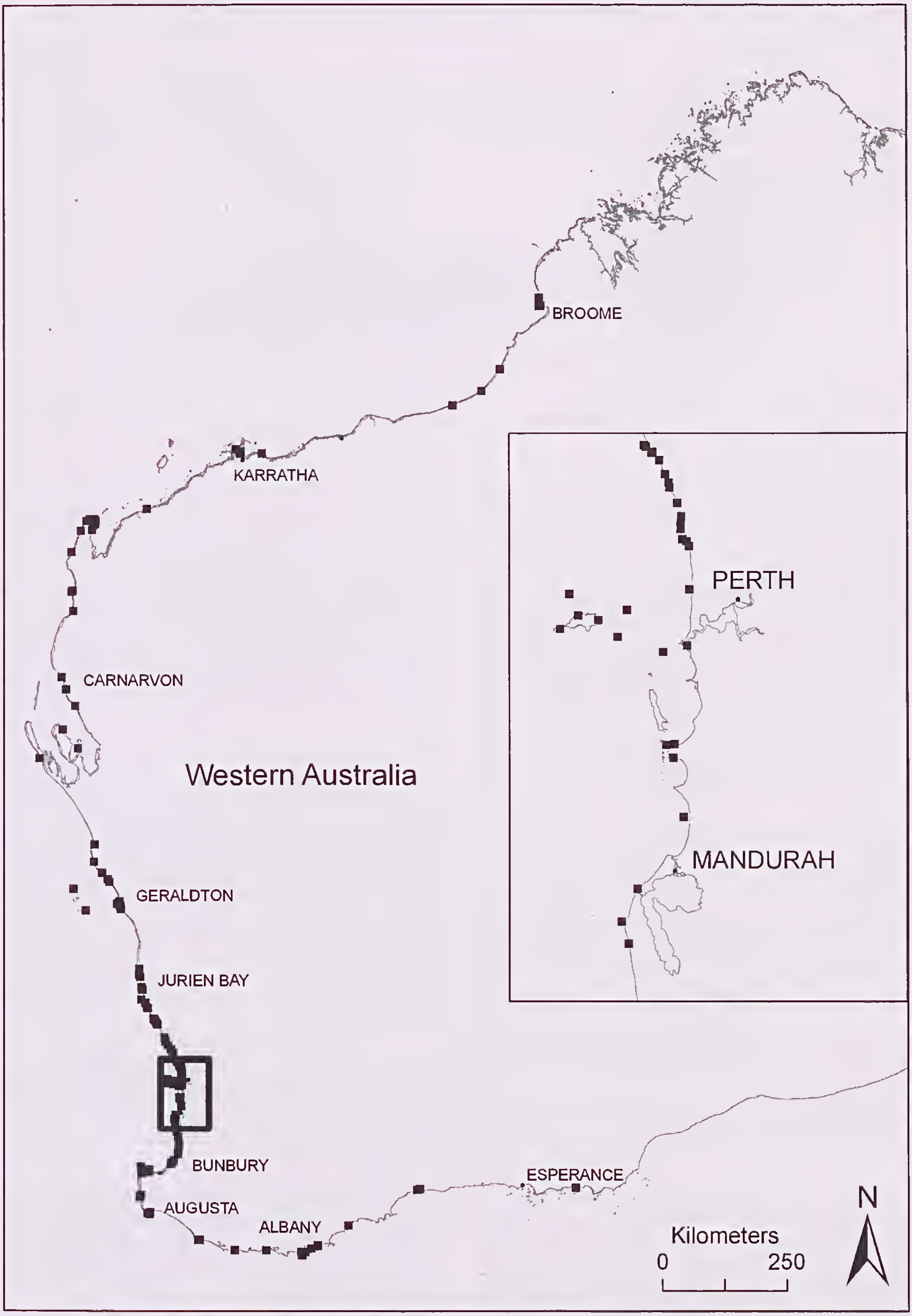


**Figure 3.** Distribution of humpback whale strandings 1981–2010.

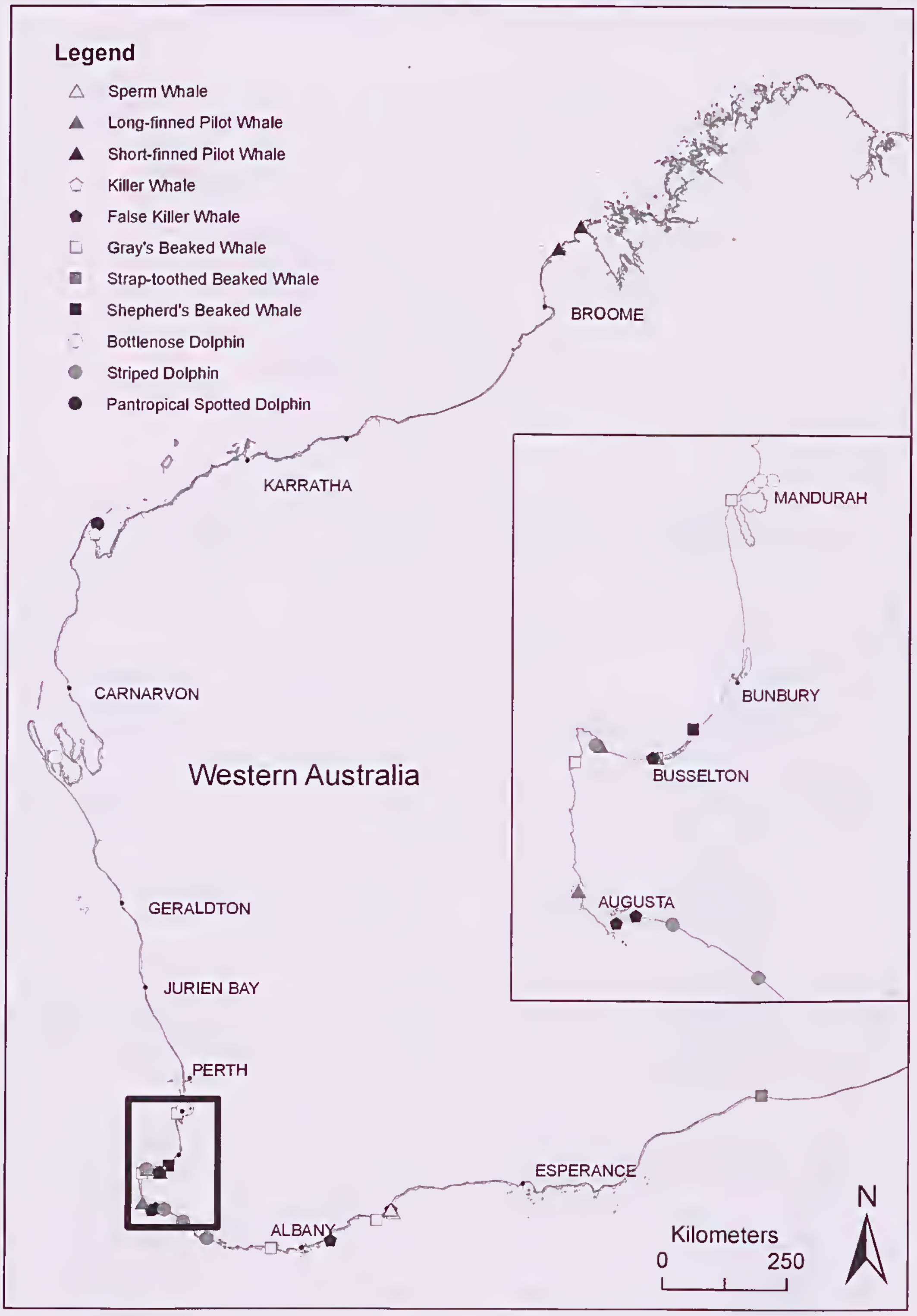


**Figure 4.** Locations of mass stranding events of cetaceans (3 or more individuals) in Western Australia 1981–2010.

### Temporal distribution of strandings

The number of stranding events recorded in the Western Australian Cetacean Stranding Database each year is shown in Figure 5. The frequency of strandings has remained relatively stable over the 29 years with 24 (± 4) events per year. An obvious exception is 2009 when an unusually high number of bottlenose dolphin (n = 36) and humpback whale (n = 46) strandings occurred.

A species with an apparent change in frequency of strandings over time is the common dolphin (*Delphius delphis*) (Figure 6). The majority of stranding events for the species occurred between 1985 and 1997 (26 events) after which only two stranding events have been recorded, both in 2010.

For each species listed in Table 3, the observed seasonal distribution of strandings was compared to an

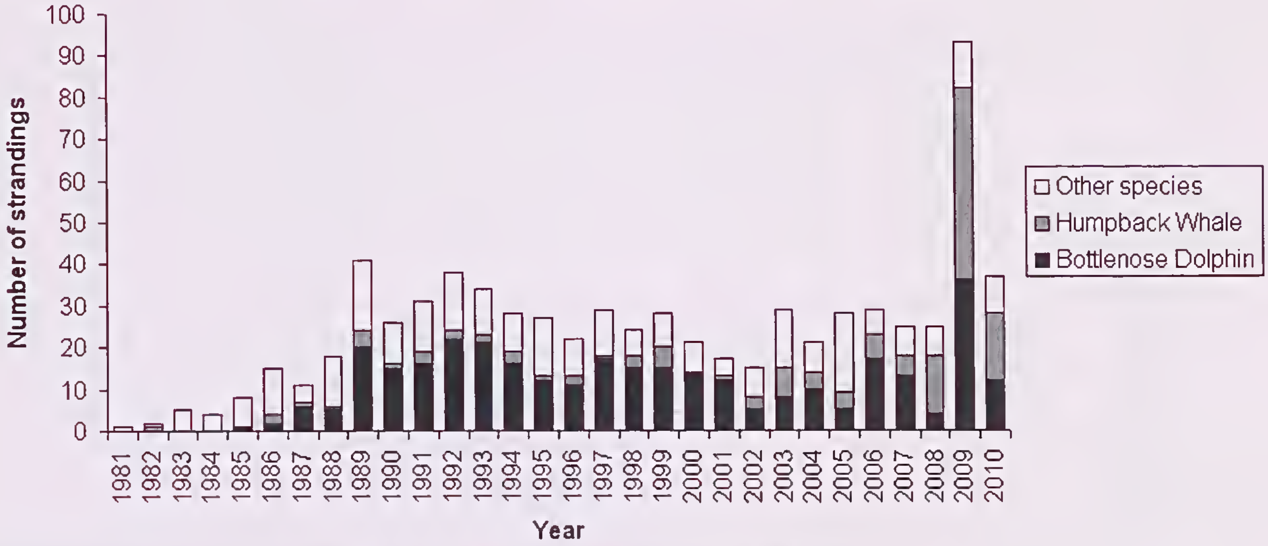


**Figure 5.** Number of cetacean stranding records for Western Australia over time 1981–2010.

expected even distribution of strandings across all seasons using a Pearson's chi-squared test. Seasonal stranding patterns differed significantly from expected even-seasonal distribution for bottlenose and common dolphins, minke, humpback and Gray's beaked whales. All other species showed no significant differences. Strandings peaked in spring for minke, humpback and sperm whales, whereas autumn was the peak for bottlenose, striped and common dolphins. Gray's beaked whale strandings peaked in summer. There were fewer strandings of dolphins in winter months than any other season.

### Outcomes and fate

Of the 1753 cetaceans stranded along the Western Australian coast between 1981 and 2010, 695 were found dead and 1047 were found alive (Table 4). Of those found alive, 70% were returned to deeper water and although the ultimate fate of those individuals is largely unknown, 6% of those returned to deeper water are known to have restranded. In an attempt to determine the fate of cetaceans returned to deeper water, individual identification numbers were freeze branded onto 65 individuals (from seven species) that were returned to deeper water. Of the animals which were freeze branded, the only individuals that were resighted were bottlenose dolphins. A few freeze branded bottlenose dolphins that inhabit the Mandurah area have stranded multiple times.

Toothed whales were much more likely to be returned to deeper water (62%) (irrespective of ultimate fate/ outcome of the individuals) than baleen whales (only 8% returned to deeper water). Most stranding records of dolphins and baleen whales were carcasses (69% of each group). A higher proportion of beaked whales were observed to strand whilst alive and subsequently die (34%) than any other group. Many of these individuals were noted in the database to have died shortly after stranding. Beaked whales were sometimes seen milling around close to shore in the days or weeks leading up to a stranding event that drew public attention and meant they were more likely to be observed soon after they stranded.

A total of 58 individuals representing 12 species were euthanased by DEC staff or veterinarians. Euthanasia was performed primarily on individuals from mass-stranding events or on baleen whales. A total of 13 individuals out of 139 strandings of humpback whales were euthanased. The technique developed for euthanasia of humpback whales through the experience of these strandings is described in Coughran *et al.*[2012 (in press)].

**Table 3** Seasonal distribution of stranding events and chi-squared values for species where the sample size of stranding events was < 20 between 1981 and 2010.

| Species | Summer Dec-Feb | Autumn Mar-May | Winter Jun-Aug | Spring Sep-Nov | $\chi^2$ | df | P |
|---|---|---|---|---|---|---|---|
| Bottlenose dolphin | 82 | 97 | 57 | 94 | 12.036 | 3 | 0.007 |
| Striped dolphin | 6 | 9 | 4 | 8 | 2.185 | 3 | 0.534 |
| Common dolphin | 8 | 14 | 3 | 7 | 11.714 | 3 | 0.008 |
| Long-finned pilot whale | 7 | 3 | 6 | 6 | 1.64 | 3 | 0.650 |
| Minke whale | 1 | 1 | 7 | 12 | 16.143 | 3 | 0.001 |
| Humpback whale | 8 | 4 | 51 | 75 | 102.754 | 3 | <0.0001 |
| Sperm whale | 9 | 5 | 8 | 12 | 2.941 | 3 | 0.401 |
| Gray's beaked whale | 17 | 4 | 1 | 0 | 33.640 | 3 | <0.0001 |

**Table 4** Outcomes and fate of individual cetaceans stranded along the Western Australian coast between 1981 and 2010.

| Species | Found dead | Died | Euthanased | Returned deeper water | Restranded and died | Restranded and euthanased | Restranded and returned to deeper water | Taken into care and died | Taken into care and returned to deeper water | Unknown | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Delphinidae** | | | | | | | | | | | |
| Indo-Pacific humpback dolphin | 4 | - | - | 1 | - | - | - | - | - | - | 5 |
| Bottlenose dolphin | 267 | 22 | 2 | 71 | 2 | - | 1 | - | - | 6 | 371 |
| Pantropical spotted dolphin | 1 | 6 | - | - | - | - | - | - | - | - | 7 |
| Striped dolphin | 54 | 20 | 2 | 12 | 1 | 1 | 5 | 1 | 1 | - | 97 |
| Spinner dolphin | 6 | - | - | - | - | - | - | - | - | - | 6 |
| Common dolphin | 27 | 1 | - | 2 | - | - | - | - | - | - | 30 |
| Fraser's dolphin | - | 1 | - | - | - | - | - | - | - | - | 1 |
| Risso's dolphin | - | 1 | 1 | - | - | - | - | - | - | - | 2 |
| Melon-headed whale | - | 1 | - | - | - | - | - | - | - | - | 1 |
| Pygmy killer whale | 1 | - | - | - | - | - | - | - | - | - | 1 |
| False killer whale | 28 | 70 | 22 | 261 | 15 | 1 | - | - | - | - | 397 |
| Killer whale | 3 | - | - | 3 | 1 | - | 1 | - | - | - | 8 |
| Short-finned pilot whale | 5 | 47 | - | - | - | - | - | - | - | - | 52 |
| Long-finned pilot whale | 92 | 24 | 3 | 319 | 4 | 3 | - | 1 | - | - | 446 |
| **Physeteridae** | | | | | | | | | | | |
| Sperm whale | 38 | 18 | 1 | - | - | - | - | - | - | - | 57 |
| **Kogiidae** | | | | | | | | | | | |
| Pygmy sperm whale | 13 | 1 | 1 | - | 1 | 2 | - | - | - | - | 18 |
| Dwarf sperm whale | 4 | - | 1 | - | - | - | - | - | - | - | 5 |
| **Balaenidae** | | | | | | | | | | | |
| Southern right whale | 6 | - | - | - | - | - | - | - | - | - | 6 |
| **Neobalaenidae** | | | | | | | | | | | |
| Pygmy right whale | 5 | - | - | - | - | 1 | - | - | - | - | 6 |
| **Balaenopteridae** | | | | | | | | | | | |
| Minke whale | 11 | 2 | 3 | 5 | - | - | - | - | - | 1 | 22 |
| Bryde's whale | 1 | - | - | - | - | - | - | - | - | - | 1 |
| Blue whale | 1 | - | - | - | - | - | - | - | - | - | 1 |
| Pygmy blue whale | 4 | - | - | - | - | - | - | - | - | - | 4 |
| Fin whale | 1 | 1 | - | - | - | - | - | - | - | - | 2 |
| Humpback whale | 95 | 19 | 13 | 7 | 1 | - | - | - | - | 4 | 139 |
| **Ziphiidae** | | | | | | | | | | | |
| Cuvier's beaked whale | 1 | 2 | - | 1 | - | - | - | - | - | - | 4 |
| Arnoux's beaked whale | 1 | - | - | - | - | - | - | - | - | - | 1 |
| Shepherd's beaked whale | 1 | - | - | 3 | - | - | - | - | - | - | 4 |
| Andrew's beaked whale | 1 | 1 | - | - | - | - | - | - | - | - | 2 |
| Blainville's beaked whale | - | 1 | - | - | - | - | - | - | - | - | 1 |
| Gray's beaked whale | 14 | 11 | 1 | 10 | 3 | - | 1 | - | - | - | 40 |
| Hector's beaked whale | 1 | 1 | - | - | - | - | - | - | - | - | 2 |
| Strap-toothed beaked whale | 5 | 2 | - | - | - | - | 1 | - | - | - | 8 |
| True's beaked whale | 4 | 2 | - | - | - | - | - | - | - | - | 6 |
| TOTAL | 695 | 254 | 51 | 695 | 28 | 7 | 9 | 2 | 1 | 11 | 1753 |

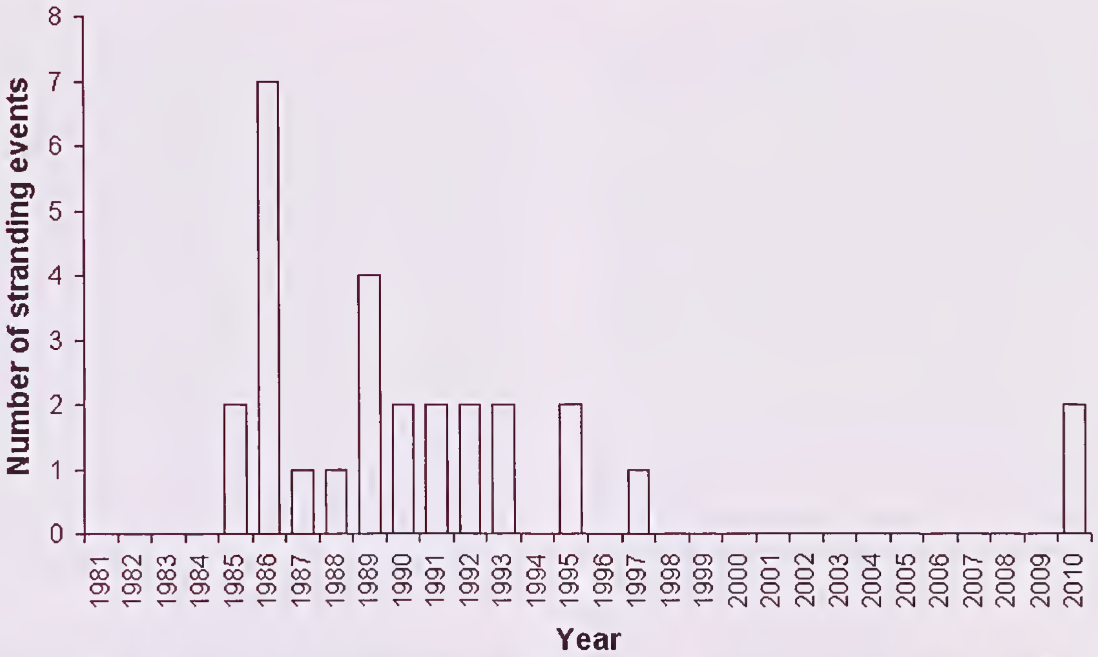


**Figure 6.** Strandings of common dolphins (*Delphinus delphis*) along the Western Australian coast between 1981 and 2010.

## DISCUSSION

The stranding data in the Western Australian Cetacean Stranding Database closely reflected the known cetacean fauna composition of the region according to Bannister *et al.* (1996) but has contributed an additional three species not previously recorded for the region. Stranding databases are known to be useful for recording rare species and have provided comparable cetacean fauna lists to at-sea sightings or boat surveys (Maldini *et al.* 2005; Pikesley *et al.* 2011). Stranding data are better at representing species not easily detected in systematic sighting surveys because of factors such as body size, surfacing behaviour or pelagic life histories (Maldini *et al.* 2005; Danil *et al.* 2010).

Stranding data can provide information on age structure (Evans *et al.* 2002; Evans & Hindell 2004). Mass strandings, where individuals are likely to be from the same social group, are particularly useful for determining age structure. However, in Western Australia, detailed or comprehensive demographic information has not been collected for mass strandings of large numbers of individuals. False killer whales and long-finned pilot whales are well-known for mass stranding and accounted for a large number of the stranded animals recorded in Western Australia in single events but only a small percentage had sex, length and other biological information recorded. This probaby reflects the logistical difficulty in taking observations and measurements from a large number of animals when the management of crowds, human safety and successful return to sea of the animals takes priority. Determination of sex may not be possible if the ventral surface and genital area is not visible and the animal cannot physically be moved.

Recording an estimate of age of stranded cetacean can provide information on age groups within species that are at higher risk of stranding. This has the potential to lead to conservation action if the cause for a particular age group being susceptible is preventable. However, it may also simply provide information on the natural mortality rates of a species. A large proportion (31%) of bottlenose dolphin strandings in Western Australia were calves. This is consistent with findings from Shark Bay that show natural calf mortality to be 44% of calves before age three (Mann *et al.* 2000). In contrast, Kemper & Ling (1991) reported that calves only accounted for 9% of bottlenose dolphin strandings in South Australia.

Stranding data can also show seasonal trends which provide information about migration or movements patterns of cetacean species (Danil *et al.* 2010). For humpback whales and minke whales in Western Australia the peak in strandings (predominantly calves) between July and November coincides with their known migratory patterns and breeding season for the region (Kasamatsu *et al.* 1995; Jenner *et al.* 2001). For Gray's beaked whale the reason for the seasonality of strandings is unknown but it may be related to ocean temperatures with the waters off the south coast and southwest corner of the State being cooler in the summer months due to ocean currents. In summer, the Leeuwin Current that brings warm water southwards is weakest and the Cape Current which brings cool water northwards around the southwest corner of Western Australia is strongest (Pearce & Pattiaratchi 1999). This means that the coastal water temperature is more comparable to the subantarctic and temperate waters that Gray's beaked whale is known to inhabit (Bannister *et al.* 1996).

The majority of common dolphin strandings occurred along the south coast between 1985 and 1995 which is a period when the seasonal catch of the west coast purse-seine fishery was high (Molony & Lai 2010). Common dolphins are known to have been taken by this fishery with 33 entanglement deaths reported between 1989 and 1994 (Gales *et al.* 2003). It is likely that some of the strandings recorded during the period were associated with the fishery (e.g. bycatch) or were attracted to the area by the same fish stocks that were being targeted by the fishery. The fishery collapsed when mass mortalities of Australian pilchards occurred in 1995 and 1998/99 (Gaughan *et al.* 2000), after which very few common dolphin strandings have been recorded.

Other studies have reported an increase in the number of strandings reported each year over time (Norman *et al.* 2004; Maldini *et al.* 2005; Leeney *et al.* 2008; Aragones *et al.* 2010; Danil *et al.* 2010). This has been attributed to an increase in the number of observers and observer effort. For Western Australia, except for 2009, the number of strandings reported each year is relatively consistent.

An unusually high number of bottlenose dolphin and humpback whale strandings occurred in 2009. The dolphin strandings included the recovery of six bottlenose dolphin carcasses within the Swan–Canning Estuary over a five-month period (Beazley 2010; Holyoake *et al.* 2010). Post-mortem examination of four dolphins found that the mortalities were associated with viral, bacterial, and/or fungal infection and identified entanglement injuries, contaminant burdens, and stress from human activities as potential contributing factors. The increase in humpback whale strandings is being investigated and will be reported elsewhere. Investigations are focusing on evidence for the population reaching carrying capacity. A large proportion (61%) of the 2009 strandings of humpback whales were calves and this bias towards very young animals stranding was also evident in 2008 and 2010.

As discussed by Norman *et al.* (2004) many factors can potentially affect the observed distribution and frequency of strandings. The most obvious factors relate to the underlying abundance of species and the probability of detection given human population density. Other factors relate to our ability to find the carcass or for it to reach the shore before it sinks, decomposes, becomes scavenged or is taken back out to sea by tides. Factors such as ocean currents, weather patterns, coastline geography and undersea topography also affect where and when a cetacean may reach the shore. All these factors make it difficult to draw conclusions about the distribution and abundance of species based on stranding data.

It is common for a greater number of strandings to be reported from areas with high human population density (Kemper & Ling 1991; Maldini *et al.* 2005). The Western Australian coastline is extensive and many areas, particularly in the north of the State, are sparsely populated. Very few strandings have been recorded from the sparsely populated Kimberley, Pilbara and Nullarbor coasts. These regions are remote and often have poor access to the coast both from the land (e.g. few roads) and from the sea (e.g. rocky shores or cliffs). It is difficult to maintain an active stranding network in sparsely populated areas and a large amount of effort would be required to extend reporting networks to be consistent along the entire coastline (Maldini *et al.* 2005). The logistics and cost of responding to strandings in remote stretches of coastline mean that many cetaceans will be found long after the initial stranding, if at all. This must be acknowledged as a limitation of the data, and must be considered in any spatial analysis of the fate of stranded animals.

Spatial and temporal patterns in observation effort may also result in a bias in the species reported or season in which most strandings are reported. The trend for a large portion of dolphin and Gray's beaked whale records to be observed in warmer months could be an artefact of a greater number of potential observers visiting and spending time on beaches during summer for recreation (Kemper & Ling 1991; Norman *et al.* 2004). The high number of reported bottlenose dolphin strandings is likely a result of the significant overlap in their preferred habitat and the coastal and estuarine areas frequented by people, but it may also be attributed to a particular interest in the community for that species. Bottlenose dolphins inhabit areas popular for water-based recreation and sometimes actively interact with fishing boats (Finn *et al.* 2008; Donaldson *et al.* 2010) and swimmers making them highly visible to people. Bottlenose dolphins are a well-studied cetacean species in Western Australia and so the high number of reported strandings may be partly a result of this concerted scientific effort and scientific interest.

The concentration of stranding records that occurred in the southwest of the State may not simply be related to observer effort and population density. The southwest corner of Western Australia has tidal and geographical features that mean there is a greater potential for strandings to occur and for them to then be observed than in the north of the State. The difference between high tide and low tide is far greater in the north of Australia, especially the Canning IMCRA bioregion (Interim Marine and Coastal Regionalisation for Australia Technical Group 1998), meaning any carcass washed ashore is likely to be washed back out to sea with the next high tide which reduces the time available to observe and report the carcass. The south coast is a complicated coastline consisting of a series of sandy lunate bays with rocky headlands that can potentially snag dead or moribund cetaceans. The continental shelf is also closer to shore in the south compared to the north of the State which increases the chance of pelagic species coming close to the coast and stranding or being washed ashore in an intact state. Kemper & Ling (1991) discuss the complexity of coastlines and shallowness of waters offshore between States in Australia in relation to the number of mass-stranding events and conclude States with shallow waters and/or an uncomplicated coastline have fewer mass strandings (i.e. South Australia, Victoria, Queensland, New South Wales).

Strandings may also be more abundant in some areas because the productivity of the marine environment is high due to certain oceanographic features such as where upwellings occur or where deep sea canyons are present (Kemper & Ling 1991). An extremely large deep sea canyon is present off Perth and there are numerous smaller canyons along the south coast (Harris *et al.* 2003). The Perth Canyon is known to promote localised upwelling and enhances both the production and physical aggregation of plankton that attracts feeding pygmy sperm whales (Rennie *et al.* 2009).

### Management implications

This study has aimed to describe the cetacean fauna of Western Australia, identify any spatial and temporal patterns of strandings and assess the outcomes of stranding events. The efficiency of the stranding reporting and response network has not been the focus of this study but it may be worthy of further investigation and review. The Western Australian Cetacean Stranding Database contains a high proportion of events where the animals were reported as stranding live (60%) and therefore required some form of assistance. In comparison, in South Australia only 15% of stranding records involved animals which were reported as stranding alive (Kemper & Ling 1991). The high proportion of live strandings reported in Western Australia is likely to be attributable to the nature of the datasets. The dataset used by Kemper & Ling (1991) utilised museum specimens whereas the dataset used for this study records incidents where a management response was required and is therefore more likely to contain live strandings where rescue was attempted. Of those found stranded alive in Western Australia, over 70% were rescued (i.e. returned to deeper water). A review of the stranding reporting and response network would be beneficial to identify aspects that work well and those that require improvement.

Each record of a stranded cetacean in the Western Australian Cetacean Stranding Database required some kind of management action by DEC. At the most basic level, the reporting of a cetacean carcass may have required an investment of time to acquire relevant information and to enter the relevant details into the database. Reports of live strandings usually required a much more elaborate management response. Based purely on the number of recorded stranding events, bottlenose dolphins and humpback whales required the largest commitment of resources in Western Australia. These two species also accounted for a large number of individuals reported stranding alive, and of the individuals requiring some form of management response such as an effort to return the animals to deeper water or to undertake euthanasia. Other notable species requiring investments of resources to support management responses were those species that mass strand, particularly long-finned pilot whales and false killer whales. Mass-stranding events require a disproportionate amount of time and resources to manage than events involving single individuals. Mass strandings involve a large number of volunteers to coordinate, significant public attention and difficult logistics to undertake the rescue operations (Edwards 1987; McNamara 1987; Mell 1988).

Management of strandings is different for each group. Dolphins and beaked whales generally strand individually or in small groups, and their physical size enables them to be handled by fewer people with less mechanical assistance. Baleen whales almost exclusively strand individually and do not lend themselves to rescue because stranded individuals are often in very poor condition and their weight and size makes moving them without injury extremely difficult. Management of baleen whale strandings primarily involves crowd management, euthanasia, appropriate carcass disposal and hygiene protocols. Toothed whales that mass strand require large logistical support to manage volunteers and coordinate rescue attempts. Having a pre-prepared general response plan for groups of cetacean species and incident types assists in providing an efficient and appropriate response.

The DEC has adopted the Australian Inter-Service Incident Management System (AIIMS) (http://knowledgeweb.afac.com.au/training/aiims accessed 2 March 2012), which provides a total systems approach to all incident management involving risk. The management system is a structure that ensures all vital management actions and procedures are undertaken properly. It is a modular structure that expands or contracts depending on the size or stage of the incident (i.e. one animal involving one person undertaking multiple tasks to multiple animals involving many people with specific tasks).

In conclusion, the study of strandings in the Western Australian Cetacean Stranding Database has provided a comprehensive list of cetacean fauna recorded in Western Australia. The dominance of bottlenose dolphins and humpback whales in the stranding record indicate that these species require particular attention to ensure management resources are allocated most effectively in the future. The spatial pattern of strandings and mass strandings confirms that the southwest of the State is currently, and will likely remain, the region of the greatest number of reported stranding events.

## ACKNOWLEDGEMENTS

We thank the numerous volunteers and staff of the Department of Environment and Conservation for collecting information on stranding events and contributing to the valuable dataset utilised for this study. Peter Mawson, Holly Raudino, Dale Roberts and journal reviewers Hugh Finn and an anonymous reviewer kindly provided advice on earlier versions of the manuscript. This project was funded through the Australian Marine Mammal Centre of the Australian Antarctic Division as part of a program to develop an Australian National Marine Mammal database.

## REFERENCES

Anonymous 1981. Dolphins die after stranding near Cape Leeuwin. *Swans* **11**, 30–31.

Aragones L V, Roque M A A, Flores M B, Encomienda R P, Laule G E, Espinos B G, Maniago F E, Diaz G C, Alensa E B & Braun R C 2010. The Philippine mammal strandings from 1998 to 2009: animals in the Philippines in peril? *Aquatic Mammals* **36**, 219–233.

Bannister J L, Kemper C M & Warneke R M 1996.*The action plan for Australian cetaceans*. Australian Nature Conservation Agency, Canberra.

Beazley L 2010. Dolphin deaths in the Swan Canning Riverpark and comments on the Bunbury inner waters, South-west of Western Australia. Report to the Minister for Environment <http://www.swanrivertrust.wa.gov.au/science/river/Documents/Dolphin_Review_Final_30_April_2010.pdf>.

Bogomolni A L, Pugliares K R, Sharp S M, Patchett K, Harry C T, La Rocque J M, Touhey K M & Moore M 2010. Mortality trends of stranded marine mammals on Cape Cod and southeastern Massachusetts, USA, 2000 to 2006. *Diseases of Aquatic Organisms* 88, 143–155.

Charlton-Robb K, Gershwin L-A, Thompson R, Austin J, Owen K & McKechnie S 2011. A new dolphin species, the Burrunan Dolphin *Tursiops australis* sp. nov., endemic to southern Australian coastal waters. *PloS ONE*6, e24047.

Commonwealth of Australia 2006.*A guide to the integrated marine and coastal regionalisation of Australia Version 4.0.* Department of Environment and Heritage, Canberra.

Coughran D K, Stiles I & Mawson P R 2012 (in press). Euthanasia of beached humpback whales using explosives. *Journal of Cetacean Research and Management* 12, 137–144.

Danil K, Chivers S J, Henshaw M D, Theileking J L, Daniels R & St Leger J A 2010. Cetacean strandings in San Diego County, California, USA: 1851–2008. *Journal of Cetacean Research and Management* 11, 163–184.

Donaldson R, Finn H & Calver M 2010. Illegal feeding increases risk of boat-strikes and entanglement in bottlenose dolphins in Perth, Western Australia. *Pacific Conservation Biology* **16**, 157–161.

Edwards H 1987. Rescue Augusta. *Far Horizons* Jan-Feb 1987, 12–15.

Evans K & Hindell M A 2004. The age structure and growth of female sperm whales (*Physeter macrocephalus*) in southern Australian waters. *Journal of Zoology* **263**, 237–250.

Evans K, Morrice M, Hindell M A & Thiele D 2002. Three mass strandings of sperm whales (*Physeter macrocephalus*) in southern Australian waters. *Marine Mammal Science* **18**, 622–643.

Finn H, Donaldson R & Calver M C 2008. Feeding Flipper: a case study of human–dolphin interaction. *Pacific Conservation Biology*14, 215–225.

Gales N J 1992. Mass stranding of striped dolphin, *Stenella coeruleoalba*, at Augusta, Western Australia: notes on clinical pathology and general observations. *Journal of Wildlife Diseases* **28**, 651–655.

Gales N J, Hindell M A & Kirkwood J K 2003. *Marine mammals: fisheries, tourism and management issues.* CSIRO Publishing, Collingwood.

Gaughan D J, Mitchell R W & Blight S J 2000. Impact of mortality, possibly due to herpesvirus, on pilchard *Sardinops sagax* stocks along the south coast of Western Australia in 1998–99. *Marine and Freshwater Research* **51**, 601–612.

Hale P T, Barreto A S & Ross G J B 2000. Comparative morphology and distribution of the *aduncus* and *truncatus* forms of bottlenose dolphin *Tursiops* in the Indian and Western Pacific Oceans. *Aquatic Mammals* **26**, 101–110.

Harris P, Heap A, Passlow V, Shaffi L, Fellow M, Porter-Smith R, Buchanan C & Daniell J 2003. Geomorphic features of the continental margin of Australia. *Geoscience Australia Record* **2003/30.**

Hoelzel A R, Potter C W & Best P B 1998. Genetic differentiation between parapatric 'nearshore' and 'offshore' populations of the bottlenose dolphin. *Proceedings of the Royal Society of London* **B265**, 1177–1183.

Holyoake C, Finn H, Stephens N, Duignan P, Salgado C, Smith H, Bedjer L, Linke T, Daniel C, Moiler K, Nam H, Ham GS, Allen S, Bryant K & McElligott D 2010.Technical report on the Bottlenose Dolphin (*Tursiops truncatus*) unusual mortality event within the Swan Canning Riverpark, June-October 2009. Marine Mammal Health Project. Murdoch University, Perth <http://www.swanrivertrust.wa.gov.au/science/Documents/2010-06-09%20Swan%20Dolphin%20Technical%20Report_final%20part1.pdf>.

Interim Marine and Coastal Regionalisation for Australia Technical Group 1998. *Interim Marine and Coastal Regionalisation for Australia: an ecosystem-based classification for marine and coastal environments. Version 3.3.* Environment Australia, Commonwealth Department of the Environment, Canberra,

Jenner K C S, Jenner M & McCabe K A 2001. Geographical and temporal movements of humpback whales in Western Australian waters. *APPEA Journal* **41**, 749–765.

Kasamatsu F, Nishiwaki S & Ishikawa H 1995. Breeding areas and southbound migration of southern minke whales *Balaenoptera acutorostrata. Marine Ecology Progress Series* **119**, 1–10.

Kemper C, Flaherty A, Gibbs S, Hill M, Long M & Byard R W 2005. Cetacean captures, strandings and mortalities in South Australia 1881–2000, with special reference to human interactions. *Australian Mammalogy* **27**, 37–47.

Kemper CM & Ling JK 1991. Whale strandings in South Australia (1881–1989). *Transactions of the Royal Society of South Australia* **115**, 37–52.

Leeney R H, Amies R, Broderick A C, Witt M J, Loveridge J, Doyle J & Godley B J 2008. Spatio-temperal analysis of cetacean strandings and bycatch in a UK fisheries hotspot. *Biodiversity Conservation* **17**, 2323–2338.

MacCleod C D, Bannon S M, Pierce G J, Schweder C, Learmonth J A, Herman H A & Reid R J 2005. Climate change and the cetacean community of north-west Scotland. *Biological Conservation* **124**, 477–483

MacLeod C D, Perrin W F, Pitman R, Barlow J, Ballance L, D'Amico A, Gerrodette T, Joyce G, Mullin K D, Palka D L & Waring G T 2006. Known and inferred distributions of beaked whale species (Cetacea: Ziphiidae). *Journal of Cetacean Research and Management* **7**, 271–286.

Maldini D, Mazzuca L & Atkinson S 2005. Odontocete stranding patterns in the Hawaiian Islands (1937–2002): how do they compare with live animal surveys? *Pacific Science* **59**, 55–67.

Mann J, Connor R C, Barre L M & Heithaus M R 2000. Female reproductive success in bottlenose dolphins (*Tursiops sp.*): life history, habitat, provisioning, and group size effects. *Behavioural Ecology* **11**, 210–219.

McNamara K 1987. Saving the whales. *Landscope* **2**, 3–18.

Mell D J 1988. An operational perspective of the rescue of false killer whales (*Pseudorca crassidens*) stranded at Augusta in July 1986. *In:* Augee G L (ed.) *Marine mammals of Australasia: field biology and captive management,* pp. 43–57. Royal Zoological Society of New South Wales, Sydney.

Molony B & Lai E 2010. West coast purse seine fishery report: statistics only. *In:*Fletcher W J & Santoro K (eds) *State of the Fisheries and Aquatic Resources Report 2009/10,* pp. 78–79. Department of Fisheries, Perth.

Norman S A, Bowlby C E, Brancato M S, Calambokidis J, Duffield D, Gearin P J, Gaornall T A, Gosho M E, Hanson B, Hodder J, Jeffries S J, Lagerquist B, Lambourn D M, Mate B, Norberg B, Osborne R W, Rash J A, Riemer S & Scordino J 2004. Cetacean strandings in Oregon and Washington between 1930 and 2002. *Journal of Cetacean Research and Management* **6**, 87–99.

Pearce A & Pattiaratchi C 1999. The Capes Current: a summer countercurrent flowing past Cape Leeuwin and Cape Naturaliste, Western Australia. *Continental Shelf Research* **19**, 401–420.

Pikesley S K, Witt M J, Hardy T, Loveridge J, Loveridge J, Williams R & Godley B J 2011.Cetacean sightings and strandings: evidence for spatial and temporal trends. *Journal of the Marine Biological Association of the United Kingdom* DOI: 10.1017/S0025315411001470.

Rennie S, Hanson C E, McCauley R D, Pattriaratchi C, Burton C, Bannister J L, Jenner C & Jenner M-N 2009.Physical properties and processes in the Perth Canyon, Western Australia: links to water column production and seasonal pygmy blue whale abundance.*Journal of Marine Systems* **77**, 21–44.

Wang J W, Chou L-S & White B N 2000. Differences in the external morphology of two sympatric species of bottlenose dolphins (genus *Tursiops*) in the waters of China. *Journal of Mammalogy* **81**, 1157–1165.

*Received 1 November 2011; accepted 11 April 2012.*

*Journal of the Royal Society of Western Australia*

*A refereed journal for science in Western Australia*

## Instructions to Authors

The *Journal of the Royal Society of Western Australia* publishes (after refereeing)

- papers and notes dealing with original research done in Western Australia into any branch of the natural or physical sciences;
- papers and notes concerning some aspect of natural or physical science of relevance to Western Australian scientists, but not necessarily done in Western Australia;
- authoritative overviews of any subject in the natural or physical sciences with the general membership of the Society in mind;
- analyses of controversial issues of great scientific moment in Western Australia

Prospective authors of papers in the last two categories should consult the Editor for further advice. The *Journal* also publishes "Letters to the Editor" and a bibliographic summary of recent journal papers and review articles in "Recent Advances in Science in Western Australia".

Authors are encouraged to submit a list of potential reviewers in Australia or overseas, but choice of reviewers is at the discretion of the Editor. Publication in the Society's *Journal* is available to all categories of members. Submission of a paper is taken to mean that the results have not been published or are not being considered for publication elsewhere. Authors are solely responsible for the accuracy of all information in their papers, and for any opinions they express. A pdf of the published paper is provided free to corresponding authors and their coauthors; hard copy offprints may be ordered at proof stage at a rate of $100 (incl GST and postage) for 50 offprints.

**Manuscripts**. Manuscripts should be submitted as pdfs or Word (doc or docx) files to journal@royalsocietyofwa.com. All pages should be numbered consecutively, including those carrying tables and captions to illustrations. Illustrations, both line drawings and photographs, are to be numbered as figures in common sequence, and each must be referred to in the text, in consecutive order. In composite figures made up of several photographs or diagrams, each part should be designated by a letter (e.g. Figure 2b). To avoid risk of damage to the original figures, authors should retain the original figures until the paper is accepted. The copies of the figures accompanying the manuscript must be of good quality. Authors are advised to use the most recent issues of the Journal as a guide to the general format and bibliographic style of the manuscript, and to conform as closely as possible to the style in preparing the manuscript. Authors should maintain a proper balance between length and substance, and papers longer than 10 000 words would need to be of exceptional importance to be considered for publication. Electronic processing of manuscripts from disks supplied by the authors is necessary to reduce publication costs. Following acceptance and editing of the manuscript, authors should amend their manuscript and forward one printed copy of the paper and the word-processing file on computer.

**Notes.** The Society wishes to encourage scientists to publish short notes dealing with original research done in any branch of the natural or physical sciences in Western Australia, or concerning some aspect of natural or physical science of relevance to Western Australian scientists. The objective in publishing Notes is to encourage the dissemination of research findings that might not be enough for a full paper but nevertheless be of interest to other scientists, especially those in Western Australia. In addition, specific aspects of student theses, particular findings of commissioned reports, or isolated observations of significance might be well presented as a one or two page note. Notes will be restricted to a maximum length of two printed pages; notes are particularly sought as these often ensure full use of the pages available in each issue. They should generally have an Abstract, Introduction, Methods, Results and Discussion, and References sections, but the exact section organization is flexible. Photographs and figures should be suitable for single column reproduction (82mm wide) wherever possible. Manuscripts submitted as a Note will be reviewed in the same manner as full articles.

The **Title** should begin with a keyword. The **Abstract** should not be an expanded title, but should include the main substance of the paper in a condensed form. The metric system (SI units) must be used. Taxonomic papers must follow the appropriate International Code of Nomenclature, and geological papers must adhere to the International Stratigraphic Guide. Spelling should follow the Concise Oxford Dictionary.

**Keywords** or phrases should be provided (maximum of two printed lines).

**References** must be set out as follows, with journal titles spelled out in full;

| | |
|---|---|
| *Paper:* | Jackson A 1931. The Oligochaeta of South-Western Australia. Journal of the Royal Society of Western Australia 17: 17-136. |
| *Book:* | Jacobs M R 1955. *Growth Habits of the Eucalypts*. Forestry Timber Bureau, Canberra. |
| *Chapter in Book:* | Dell J 1983. The importance of the Darling Scarp to fauna. *In*: Majer J (ed.) *Scarp Symposium*, pp. 17–27. Western Australian Institute of Technology, Bentley. |

**Illustrations**. High quality illustrations are required, no larger than 300mm x 400mm, with sans serif lettering suitable for reduction to appropriate publication size (82 or 168 mm wide). Scale must be indicated on illustrations. Photographs must be good quality prints, not exceeding 168mm x 252mm. Colour figures incur a charge of $300 (incl GST) per colour page. Additional printing costs for folding maps and charts will be charged to authors: please consult the Editor before submitting these items. Figures should be also provided as high resolution (300dpi) tif, jpg, or eps files to ensure high-quality reproduction.

**Supplementary Papers**. Extensive sets of data, such as large Tables or Appendices, may be classed as a Supplementary Papers and not printed with the paper but lodged with the Society's Library (held in the Western Australian Museum, 49 Kew Street, Welshpool, WA 6106) and with the National Library of Australia (Manuscript Section, Parkes Place, Barton, ACT 2600). They should be supplied in printed and digital form (preferable as pdfs). Photocopies of a Supplementary Publication may be obtained from either institution upon payment of a fee.

Contributions should be sent to:
**Editor in chief**
**Journal of the Royal Society of Western Australia**
**104 Hensman Street**
**South Perth WA 6151**
**or (preferably) ✉ journal@royalsocietyofwa.com**

## *Also available from the Royal Society of Western Australia:*

*(Prices are ex GST; discount prices for members are in parentheses)*

| | | |
|---|---|---|
| Regular issues of the Journal (price per part) | $12 | ($8) |
| The Leeuwin Current: An Influence on the Coastal Climate and Marine Life of Western Australia (Volume 74, 1991) | $20 | ($15) |
| Plant Diseases in Ecosystems: Threats and Impacts in South-Western Australia (Volume 77, Part 4, 1994) | $20 | ($15) |
| De Laeter Symposium on Isotope Science (Volume 79 Part 1, 1996) | $20 | ($15) |
| Symposium on the Design of Reserves for Nature Conservation in South-western Australia (Volume 79, Part 4, 1996) | $20 | ($15) |
| Mini-symposium on Remote Sensing and its Applications in Western Australia (Volume 80, part 1, 1997) | $20 | ($15) |
| Granite Outcrops Symposium (Volume 80, Part 3, 1997) | $20 | ($15) |
| Centennial Issue 1897-1997 (Volume 81, Part 1, 1998) | $20 | ($15) |
| Management of Granite Outcrops (Volume 83, Part 3, 2000) | $20 | ($15) |
| Leschenault Inlet Estuary (Volume 83, Part 4, 2000) | $50 | ($35) |
| Fire and Wetlands on the Swan Coastal Plain (Volume 88, Part 3, 2005) | $20 | ($15) |
| Holocene sedimentation, stratigraphy, biostratigraphy, and history of the Canning Coast, north-western Australia (Supplement to Volume 91 Part 1 2008) | $25 | ($20) |
| Leeuwin Current Symposium 2007 (Volume 92 Part 2, 2009) | $65 | ($45) |
| The Habitats of the Western Australian soldier crab *Mictyris occidentalis* Unno 2008 (Brachyura: Mictyridae) across its biogeographical range (Supplement to Volume 92 Part 3, 2009) | $25 | ($20) |
| Symposium on Evolutionary Biology (Volume 92 Part 4, 2009) | $45 | ($35) |
| Symposium on Kimberley Marine and Coastal Science (Volume 94 Part 2 2011) | $65 | ($45) |

Please add postage and handling at the following rates:

| | Australia | Overseas |
|---|---|---|
| Regular issue | $5.00 | $6.00 |
| Thematic Issues | $6.00 | $10.00 (Surface Mail) |
| The Leeuwin Current: An Influence on the Coastal Climate and Marine Life of Western Australia | $12.00 | $18.00 (Surface Mail) |
| DeLaeter Symposium on Isotope Science | $12.00 | $18.00 (Surface Mail) |
| Granite Outcrops Symposium | $12.00 | $18.00 (Surface Mail) |
| Leschenault Inlet Estuary | $15.00 | $30.00 (Surface Mail) |
| Leeuwin Current Symposium 2007 | $12.00 | $20.00 (Surface Mail) |
| Kimberley Marine and Coastal Science Symposium 2011 | $12.00 | $32.00 (Surface Mail) |

Combined postage discounts apply, airmail POA

Please send your order, including payment (all prices in Australian dollars), to:
Honorary Treasurer, Royal Society of Western Australia, PO Box 7026, Karawara, Western Australia 6152.

*Journal of the Royal Society of Western Australia*© is published quarterly by:
The Royal Society of Western Australia, PO Box 7026, Karawara, Western Australia 6152.
✉ rswa@museum.wa.gov.au
**ISSN 0035-922X Print Post Approved PP642409/00008.**

Claims for non-receipt of the Journal should be submitted within 12 months of publication, to:
RSWA Librarian, PO Box 7026, Karawara, Western Australia 6152,
✉ rswa@museum.wa.gov.au
Address changes should be submitted to
Membership Secretary, PO Box 7026, Karawara, Western Australia 6152.

© ROYAL SOCIETY OF WESTERN AUSTRALIA 2012

This work is copyright. Apart from any use as permitted under the *Copyright Act 1968*, no part may be reproduced by any process without written permission from the Editor-in-chief of the Royal Society of Western Australia, ✉ journal@royalsocietyofwa.com. A permissions line must be provided crediting author(s) and the Journal of the Royal Society of Western Australia as the source.

Typeset and printed in Western Australia

S-1022

Journal of the Royal Society of Western Australia Volume 95 Part 1 April 2012